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CORNELL AERONAUTICAL LABORATORY, INC.

Final Report No. VC-603-P-1

THUNDERCLOUD ELECTRIFICATION STUDIES, II

20 June 1952

Contract No. N6ori-119, Task Order 13

Office of Naval Research
(Geophysics Branch)

B U F F A L O , N E W Y O R K

FORM 144-A

CORNELL AERONAUTICAL LABORATORY, INC.

BUFFALO, N. Y.

FINAL REPORT NO. VC-603-P-1

THUNDERCLOUD ELECTRIFICATION STUDIES, II

Prepared for the

Office of Naval Research
Under Contract N6ori-119, Task Order 13
Physical Sciences Division
Geophysics Branch
Code No. NR082056

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Date: 20 June 1952

Number of pages: 152

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ABSTRACT

The objective of this project was to investigate certain mechanisms that may be effective in generation of electrical charge in thunderclouds, and to conduct some auxiliary experiments. These experiments concerned (1) electrification generated upon disruption of raindrops, (2) electrification generated upon impact of snow crystals on one another, (3) investigation by means of corona points of the earth's electric field at the ground during blizzards, and (4) investigation by means of specially modified radiosondes of the earth's electric field in the upper air during blizzards.

Drops of distilled water 4 millimeters in diameter supported in a vertical wind tunnel 4x8 inches in cross section were disrupted by various means. They generated average charges of less than 10^{-13} to more than 10^{-10} coulombs per drop of both positive and negative electrification, depending critically on the method of disruption. Smooth coalescence of two drops followed by their break-up into a few large fragments yields the former value, and "complete shattering" produced by permitting drops to be injected into the air stream with a speed of one meter per second after a free fall of 5 centimeters yields the latter. These magnitudes (the larger is two orders of magnitude greater than Simpson classical datum) are sufficient to account either for a negligible fraction of thundercloud electrification, or for all of it, respectively.

A new elementary model of thundercloud electrification, not complete in all respects and inadequate in others, is worked out. It is based upon the assumption that thundercloud turbulence is sufficient to yield the 10^{-10} coulomb-per-drop value for electrification. Separation of charge is postulated to depend on preferential capture of these shattered-drop-produced-ions by large raindrops in the earth-plus-thundercloud electric field. Drops breaking in strong electric fields would be expected to separate charges of comparable but somewhat lesser amount because of simple polarization charges on the drops.

Some experiments on 5×10^{-4} normal HCl, KOH, and KCl solutions in place of water showed nothing remarkable. Drop-breaking experiments on water drops 3mm in diameter super-cooled to -6°C yielded average charges of 6.8×10^{-12} coulombs per drop. Otherwise similar drops at 14°C yielded average charges of 6.3×10^{-12} coulombs per drop. In all cases the magnitudes of electrification vary widely from drop to drop by a factor of 100 or more, so that runs must consist of many drops if significant statistics are to be achieved.

It is concluded that the breaking-drop-processes cannot be ruled out as thundercloud charge mechanisms on the basis of alleged inability to generate sufficient charge.

Apparatus is described for measuring the electrification of snowflakes on impact with each other, and for photographing the impacting snowflake. The snow season unfortunately was over before significant results could be obtained. In work of this type it is of the greatest importance to observe what type of snowflake is involved.

Corona-point records were obtained for 22 months as a measure of the earth's electric field. Current commonly was as much as 10 microamperes in points 32 and 54 feet above ground, and occasionally was more than 20 microamperes. Results during disturbed weather were of principal interest, since under normal circumstances the corona current is zero. Even in the absence of lightning, the earth's field fluctuates markedly in magnitude and polarity over intervals of a few seconds during disturbed weather, sometimes undergoing several reversals within a few minutes. In one case during a snowstorm, it varied from -10 to +10 times normal within a minute, with no observable change in the storm. Lightning, rain, and snowstorms give recognizable corona patterns, although the latter two are rather similar. Commonly the records for a given storm show marked asymmetry in time, indicating horizontal inhomogeneities in the storm-cloud structure. There is remarkable coherence in time between records from two points 1.7 miles apart irrespective of wind direction, indicating that the agencies responsible for electrification have dimensions measured in miles. Several typical corona records are shown.

Radiosondes modified to measure the vertical component of the earth's electric field by means of the corona current to points carried by the radiosonde and trailing from it at the end of a conducting string several hundred feet long, were sent into snow clouds. The electric field records showed that electrical effects are not local to the ground. The field commonly reversed in polarity once or twice within 10,000 feet of the ground. In one case its polarity was opposite to that of the fair weather field as high as 10,000 feet. Computed magnitudes of field were only a few hundred volts per meter, which may be a consequence of misinterpretation of extrapolation of calibration, or more likely is associated with the fact that for the four cases reported, the corona currents at the ground were unusually small, about a microampere, indicating that the region traversed by the radiosondes unfortunately was inactive electrically.

Electronic equipment developed for or used in these investigations is described in detail. Notable among the twenty equipments are the DC amplifiers having a stability of one millivolt drift per day, with an input resistance of 10^{13} ohms or less, full scale output deflection of one milliampere for 15 millivolts input, easily capable of measuring 10^{-14} amperes; and the bipolar logarithmic amplifiers which had ranges of five decades for both polarities of current, but which were used only over the range of +100 to +0.1 to 0 to -0.1 to -100 microamperes for the corona current measurements.

It is suggested that the reader read Chapter VII next if he wishes to read only a summary of the project work. Chapter VIII contains a summary of recommendations.

I. INTRODUCTION

Objective

The objective of this project was to investigate certain mechanisms that may be effective in generation of electrical charge in thunderclouds, and to conduct some auxiliary experiments. These experiments concerned

(1) electrification generated upon disruption of raindrops,
(2) electrification generated upon impact of snow crystals on one another,
(3) investigation by means of corona points of the earth's electric field at the ground during blizzards, and
(4) investigations by means of specially modified radiosondes of the earth's electric field in the upper air during blizzards.

The fundamental mechanisms of thundercloud electrification definitely were not understood at the outset of this project in spite of the fact that for many years the problem had been under investigation. The only certain statement that one could make was that all of the traditional theories either were wrong or seriously incomplete. Details of each aspect of the problem are discussed later in this report in appropriate chapters.

Staff members of the Cornell Aeronautical Laboratory, formerly at Stanford University, had conducted various preliminary investigations of thundercloud electrification including some studies of electrification of breaking raindrops, electrification produced by snow crystals on impact with each other, and radiosonding investigations in thunderstorms both in Ohio and New Mexico to measure the earth's electric field. The present contract between Cornell Aeronautical Laboratory and the Office of Naval Research, N6ori-11913, was intended to be an extension of contract N6onr-251-viii with Stanford University (ref. 4).

Transfer of Equipment

Unfortunately the contract with Stanford University expired in October 1948 and the present contract did not become active until the first of January 1949. Consequently, there was a period of time when the Stanford project inventory was not under the specific jurisdiction of anyone interested in the work. It was a stipulation of the present contract that the entire Stanford project inventory be transferred to Cornell Aeronautical Laboratory immediately. Many efforts were made and much expense incurred in the form of time charges under the present contract in efforts to obtain transfer of the inventory. Three visits were made to Stanford University by Cornell Laboratory personnel who were on the west coast. No significant shipment was made by the University until August 1949. A considerable portion of the inventory never was transferred and had to be replaced, and much of the equipment that was shipped was received in damaged condition and had to be rebuilt. In retrospect it turns out that it would have been less costly to abandon the Stanford inventory at the outset, and to rebuild or replace everything from scratch.

The only purpose in mentioning these unhappy events is to place them in proper perspective in regard to the financial overrun on the original contract, which resulted in forced suspension of activities during the critical and most interesting portion of the winter season (November 1949-February 1950) when the snow work should have been carried on. On funds advanced by Cornell Laboratory, work was resumed in February, although it was not until March that the sponsor could process the necessary paper work to restore the project to financial solvency. Most of the interesting weather during the winter (December to February) went by while there was no financial support against which project time charges could be made, though a few activities were carried on "after-hours" by interested project personnel.

General Remarks

The discussion of the several parts of the project is carried out in various chapters of the report whose titles are self-explanatory.

The bibliography consists of only 40 titles. As mentioned in the bibliography, two of the references therein contain nearly 500 other references. Probably the present bibliography is adequate. References to the bibliography are indicated by number throughout the text.

Acknowledgment

Two sections of the present report were carried out under Cornell Aeronautical Laboratory internal research funds. These sections are appropriately marked in this report, and are included in it as kind of dividend, because of the intrinsic interest of their subject matter to this report.

Acknowledgment is made of participation in the project by Messrs. Leonard Bogdan, Francis Breeden, Leon Clark, Donald Haney, and Charles Kiefer, all of Cornell Aeronautical Laboratory, who were responsible on a part-time basis for certain segments of the project work.

II. RAINDROP TUBE EXPERIMENTS

Background

Simpson's classical bipolar theory of thundercloud electrification (ref. 33) was based on the well-known "water-fall electricity" phenomenon or "spray electrification" effect, in which it had been observed that when the surface of water was violently disrupted (as in a spray process), the bulk of the water became positively electrified and the air became negatively electrified. Simpson supposed that the negatively charged air was blown to the top of the thundercloud by the vertical updraft, and the positively charged rain remained below, yielding a bipolar cloud--negative on top and positive below. In his balloon soundings with the altielectrograph in the mid-thirties, Simpson discovered, nevertheless, that the top of the thundercloud was positively charged. Most of the bottom of the cloud was negatively charged, but there was a region below the main part of the cloud which was positively electrified in the heavy rain. The observed polarity of the main charge centers was in accordance with Wilson's induction theory (ref. 42). Wilson's supporters tended to ignore two significant points, however, that the lower positive charge center did exist and was not part of the Wilson theory, and that quantitative calculations as to the origin of the charges would have shown that ionization available in the atmosphere could not account for the observed electrification of thunderclouds even if all of it were separated by the Wilson mechanism. Quantitatively, Simpson's theory was based on breaking drop measurements made by Simpson in 1909 in which the average electrification per broken drop was found to be 1.6×10^{-12} coulombs. Most of the experiments were conducted in such a way that a negative charge in the air with no admixture of positive charges would not have been distinguished from a net negative charge in the air.

From experiments conducted in 1937, Chapman (ref. 7) had been aware that the magnitudes of electrification observed in spray and bubbling processes

depended very critically on the "violence" of the spraying or bubbling as well as upon the presence of very dilute contaminants, for example, 10^{-5} normal salt solution. On the hypothesis that the negative net charge observed in air in the spray process in thunderclouds was composed of a nearly equal combination of positive and negative charges with negative slightly predominating (as was the case in some laboratory spraying investigations), Chapman had conducted an investigation for the Office of Naval Research on spray experiments in a vertical wind tunnel in which the drop breaking conditions would resemble as closely as possible those in thunderclouds. For example, all previous experiments had been done in ways differing essentially from those in thunderclouds, for instance, by allowing a water drop to fall on a capillary stream of compressed air which would disintegrate the drop. The experiments by Chapman at Stanford University (refs. 4 and 5) with the vertical wind tunnel described below showed that 20×10^{-12} coulombs of both signs of electrification appeared in the air on the average per broken drop, with the negative charge slightly predominating under the conditions of the experiments. If the positive and negative electrification produced in the air by the spray mechanism could be separated by some other means, for instance, the Wilson process, then the magnitudes of charge observed in lightning discharges could be accounted for (average 24 coulombs per flash with a frequency of one flash as often as 5 seconds (ref. 6).

Statement of the Problem

Since the data obtained at Stanford University had been taken for only a single condition of air speed, humidity, drop size, etc., it had seemed desirable to extend the work at Cornell Aeronautical Laboratory so as to determine whether or not the magnitudes of charge obtained under a variety of conditions would be adequate to explain thundercloud electrification.

Brief Description of the Raindrop Tube

The equipment used at Cornell Aeronautical Laboratory was essentially

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Brief Description of the Raindrop Tube

The equipment used at Cornell Aeronautical Laboratory was essentially

similar to that used at Stanford, though much of the Stanford equipment was never transferred and had to be replaced. The basic essentials of the raindrop tube are shown in outline form on Figure 2-4. Air from two independent blowers is blown into the bottom of the two sections of the vertical raindrop tube. One section is 4 x 8 inches in cross section and remains uniform throughout the length of the tube. The other section is 4 x 4 inches in cross section at the bottom and tapers to 4 x 8 inches in the middle of the raindrop tube, introducing a velocity gradient corresponding to a factor of two in velocity. The two 8-inch-wide sections in the middle of the tube come together to form a combined open wind tunnel 8 x 8 inches in cross section. In the tapered section the vertical airspeed is sufficiently uniform to float water droplets for intervals greater than one-half hour if desired. Eventually of course, water drops evaporate sufficiently to be blown away. Water drops may be introduced into the tube through an inlet tube which shields the drops from the vertical updraft so that the drops have an appreciable velocity of fall before they reach the updraft. The over-all length of the vertical wind tunnel is approximately 13 feet.

Droplets may be broken in the tapered section by giving them several inches of free fall in the inlet tube and by maintaining a fairly high vertical air velocity, for example, 10 meters per second. Drops may be made to float by reducing the vertical air velocity so that the speed is approximately 8 meters per second about midway up the tapered section. As many as three drops may be made to float in the tapered section at one time, but even two drops will not remain independent for very long, and are likely to coalesce within a matter of 10 to 20 seconds unless one drop differs markedly in size from the other.

When drops coalesce the volume of the combination almost invariably is less than that of either drop alone so that considerable fragmentation must have occurred during the process. The spray particles are blown vertically from the tapered section into the measuring section of the raindrop tube. A horizontal electric field between the two plates of the tube drives the

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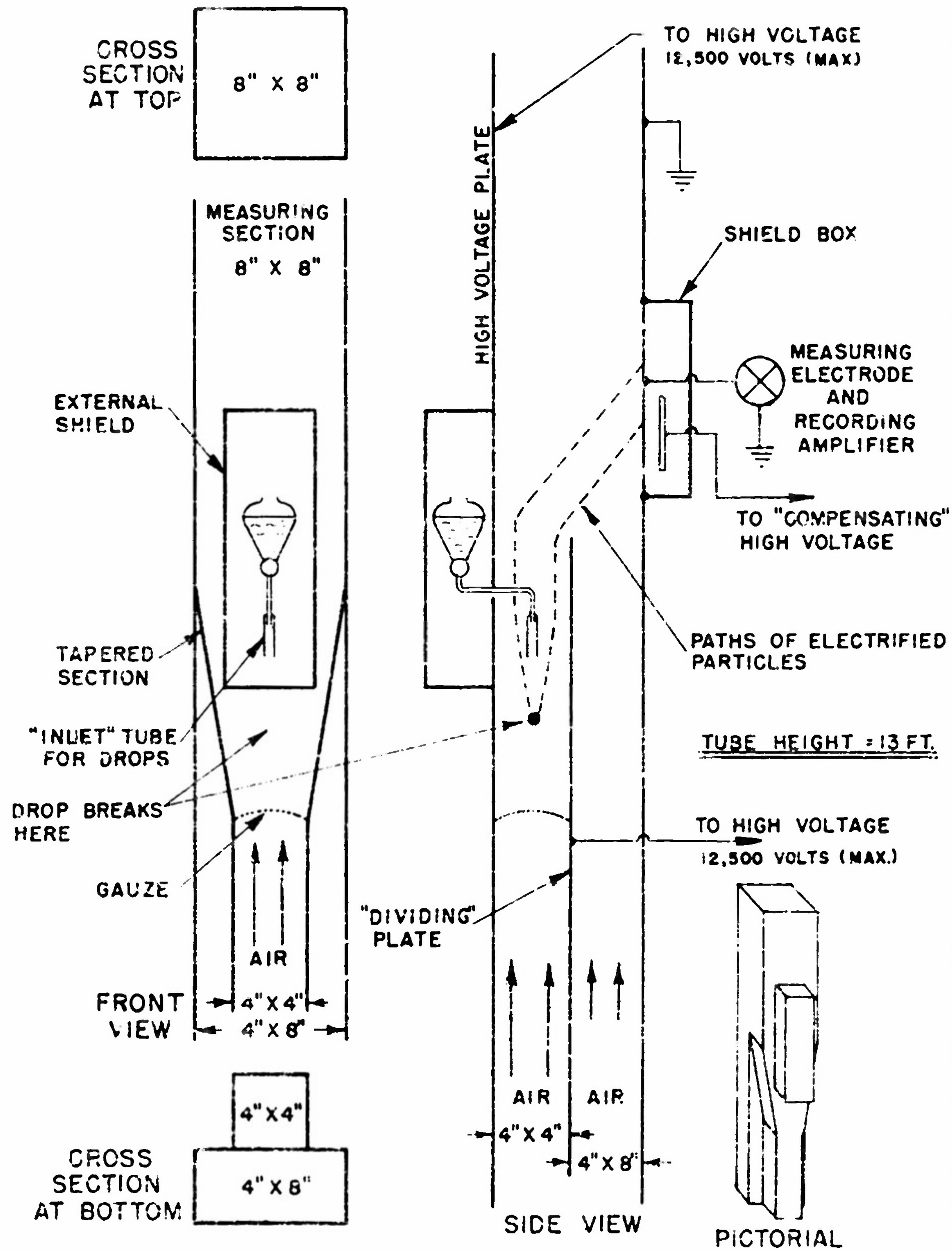

RAIN DROP TUBE

FIGURE 2-4

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electrified particles to a measuring electrode. The charge deposited on the electrode when a particle reaches it is recorded by means of amplifier-recorder instrumentation. The record consists of a series of pulses having an essentially instantaneous build-up as the charged carrier strikes the electrode, followed by an RC decay time of about 5 seconds, (i.e. the product of the electrode and amplifier capacitances and the amplifier grid resistor of about 10^{11} ohms). See illustration in Figure 4-9.

In the tapered section, the drops break in a field-free region since the dividing plate, which divides the two sections of the raindrop tube from each other, is connected to the high voltage source along with the high voltage plate. The drops ordinarily are formed from commercially available distilled water contained in a chemically clean, all-glass system. One face of the tapered section is a partially-silvered plate of glass through which one may observe break-up of the drops while maintaining a field-free region within the raindrop tube. The raindrop tube is made mainly of brass, and red wood coated with paraffin. Brass is used for the high voltage plate, the dividing plate, and the ground plate. Wood at the sides of the tube is used to separate the high voltage plate from the ground plate.

The objective of the experiment is to measure the electrification separated when drops are disrupted. When drops are disrupted, occasionally spray hits the walls or supports. One may ask whether the usual measurements are of drop breaking-electrification or drops-hitting-the-wall-electrification. Several lines of argument lead to the interpretation that the drops which hit the walls do not distort the results. In the first place, numerous experimenters agree that surface disruption causes electrification. When tiny spray particles hit the wall, ordinarily they stick and are not disrupted. Further when we have observed drops to hit the walls, even large drops, ordinarily no electrification is measured. The cross-sectional area intercepted by supports is quite small, and the small particles of high mobility which are the only ones measured are likely to follow the streamlines quite closely, and thus not hit the supports and walls. Finally, the

typical recorder trace for a breaking drop has certain characteristics (rate of rise, time at peak deflection, rate of decay) which differentiate it from occasional anomalies. On the whole, therefore, we feel confident that the results have validity.

Detailed Description of the Raindrop Tube

Though Figure 2-4 shows a single electrode connected to a recording amplifier, actually there were three electrodes which might be used independently. Further details are shown in Figures 2-7 and 2-8. The electrodes may be moved vertically from the middle of the raindrop tube to the top, so as to obtain particles having different mobilities.

Air for the raindrop tube was supplied by two blowers. One of these was a size 23 Buffalo Forge Volume Fan driven by a five horsepower motor at 3450 rpm. This blower furnished the air supply to that section of the raindrop tube where the water drops were suspended. Airstream velocity was regulated by partially blocking the inlet to the blower. The auxiliary blower was a Buffalo Forge Baby Vent type blower (BF48C) powered by a one-third horsepower motor at a speed of 1725 rpm.

Ordinarily, the air was drawn from within the Laboratory, but by connection to a port in the outside wall of the laboratory, for certain experiments air could be drawn from the outside atmosphere. On cold winter days to work at reduced temperature, air temperature could be controlled by adjustable shutters on the intakes, and its velocity could be measured by means of permanently installed Pitot-tube water-manometers.

Voltage Supply

The high voltage was provided by means of an arrangement (see Figure 2-9) employing a 10,000-0-10,000 volt neon sign transformer fed by a Variac. Type 8013A rectifiers were used. The output was filtered by two 20,000 volt 0.25 microfarad capacitors. Across each leg of the power supply there was a 200

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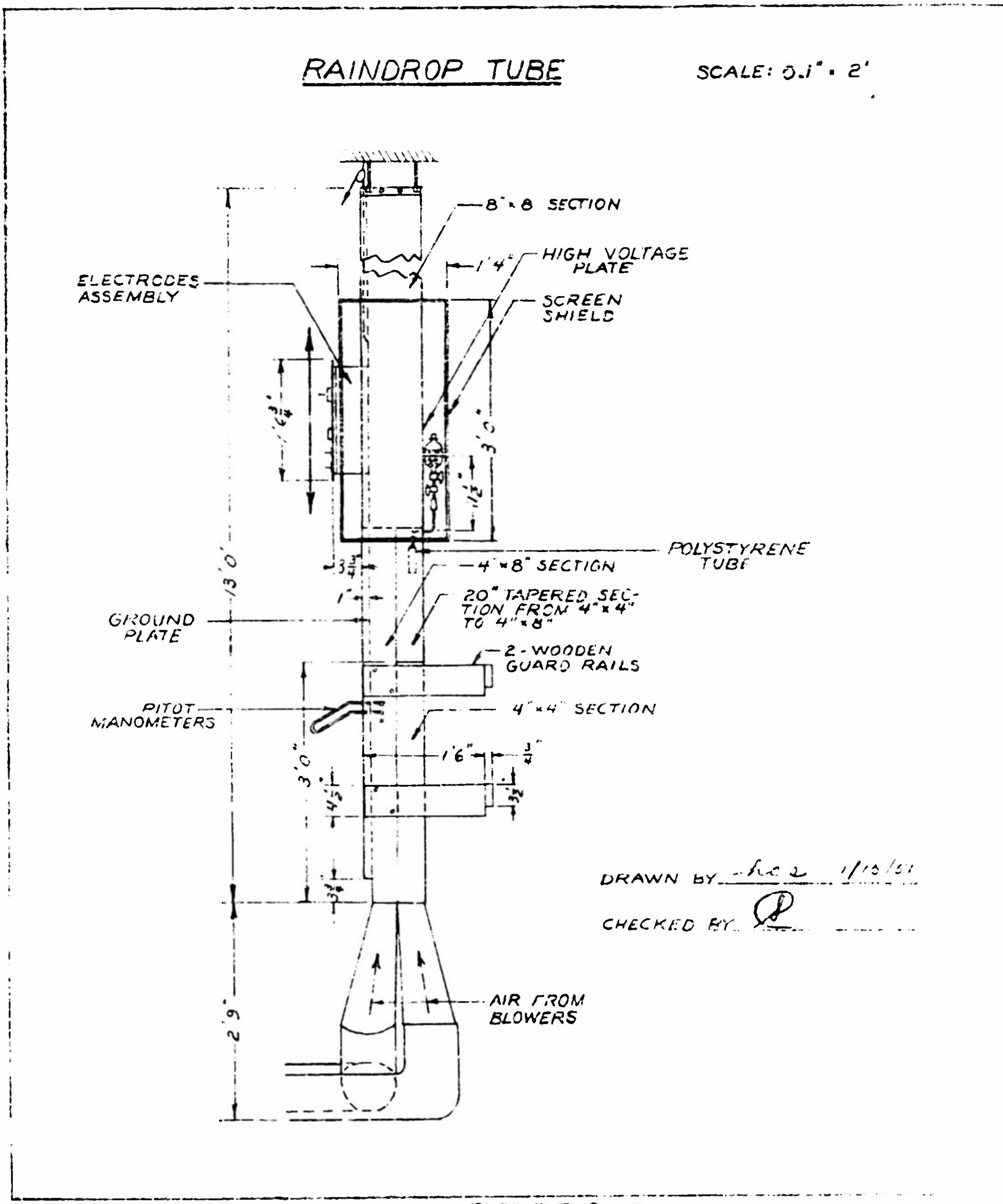

FIGURE 2-7

ELECTRODES ASSEMBLY OF RAINDROP TUBE

SCALE: 0.2" = 1"

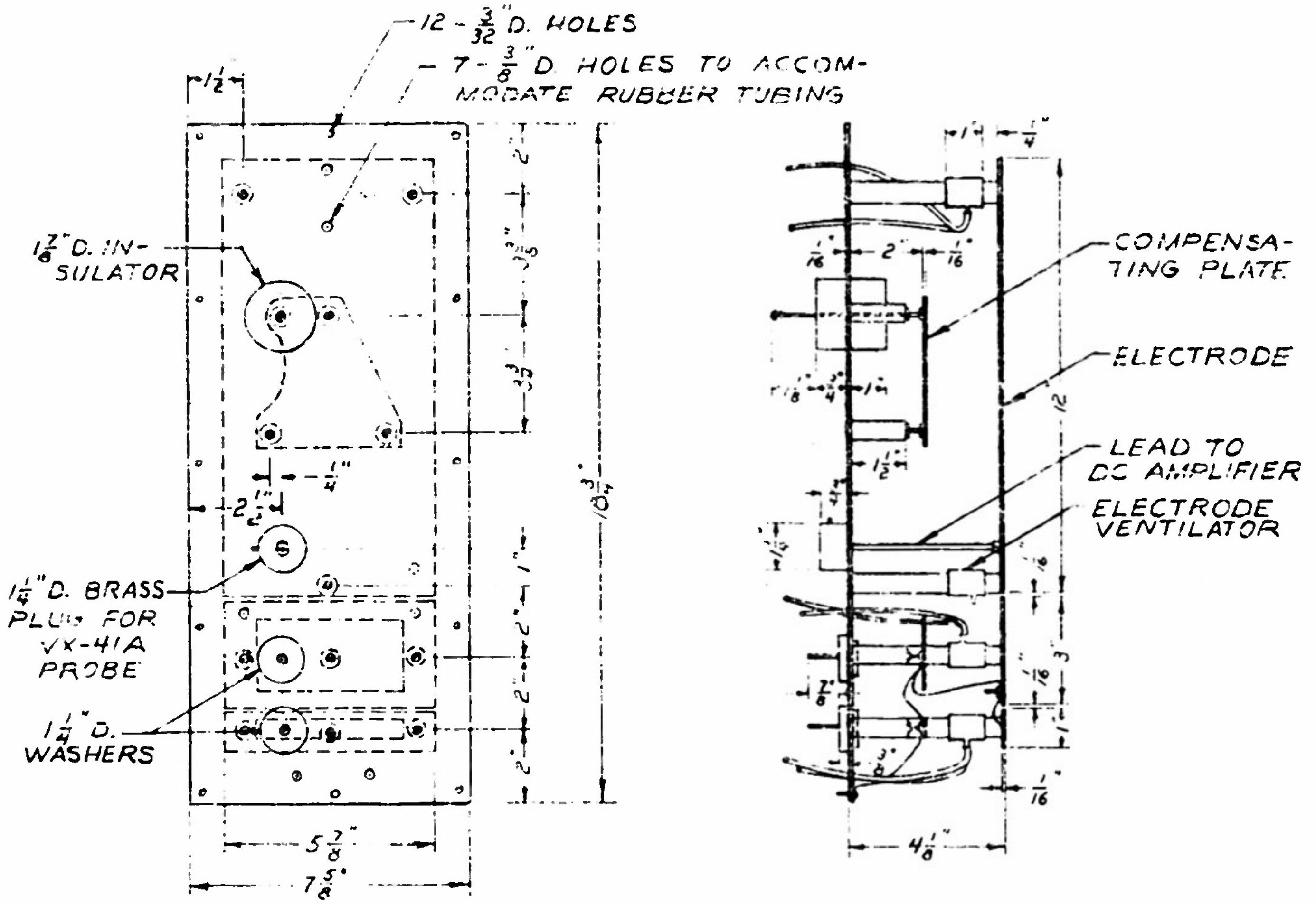

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FIGURE 2-8

FORM 145 (REV. 6-48)

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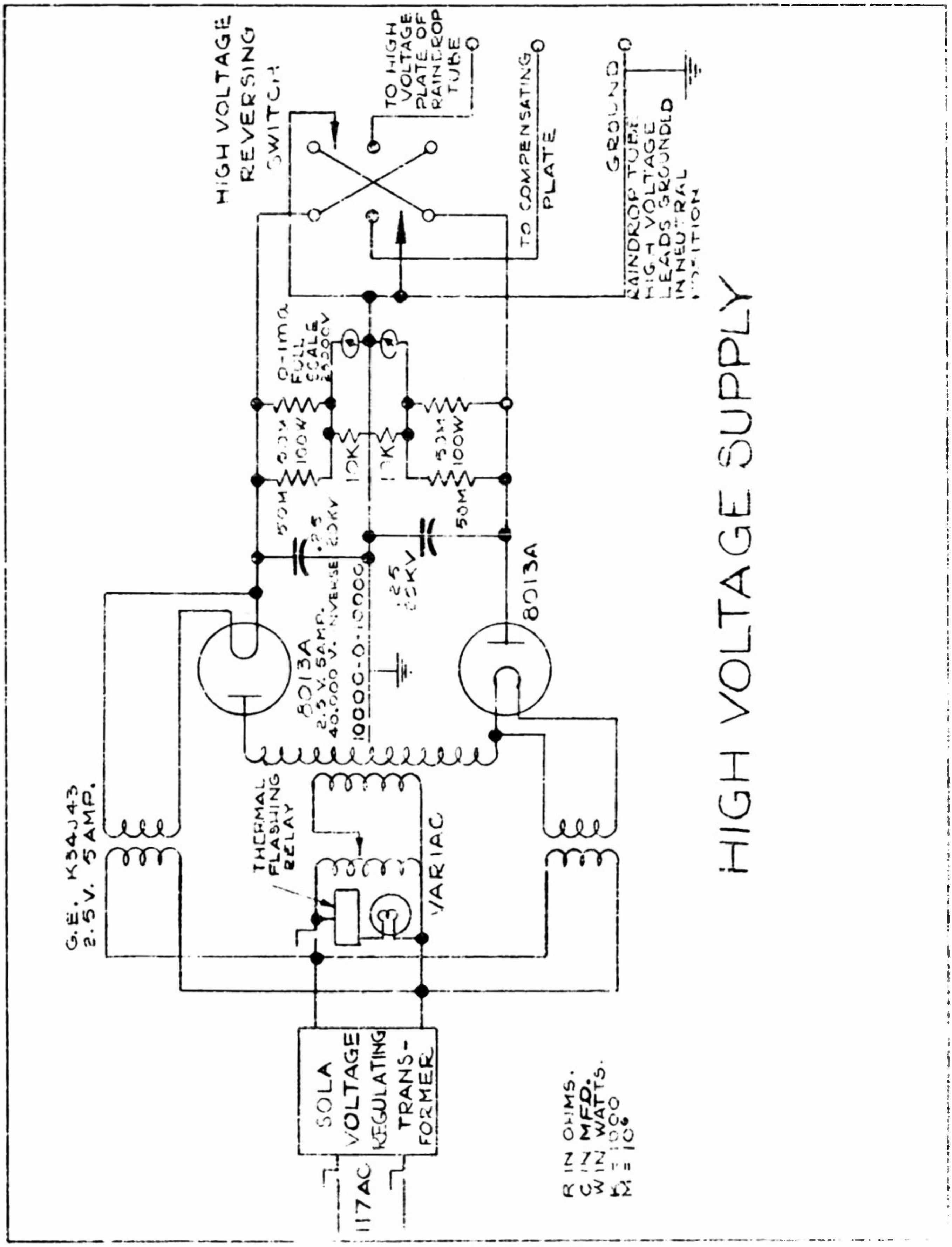


FIGURE 2-9

watt bleeder of 25 megohms. The supply was arranged to generate equal voltages of both polarities at the same time. Through a high-voltage reversing switch* which grounded both output leads when it was in the neutral position, one polarity of the high voltage was connected to the high voltage plate of the raindrop tube, and the other was connected to a compensating plate placed near the measuring electrode.

The capacitance of the compensating plate to the measuring electrode was adjusted to be equal to the capacitance of the high voltage plate to the measuring electrode. Since both high voltage outputs came from the same voltage supply, line voltage variations in the supply, or even changes in the Variac setting, induced relatively little charge on the measuring electrode. For example, when capacitances were balanced properly, changes in the high voltage of the order of 1,000 volts induce a potential of less than half a volt on the measuring electrode.

The measuring electrode was large (8x12 inches) and therefore had to be protected from 60 cycle pickup by a rather large screen. Ordinarily, the grid resistor of the input circuit was 10^{11} ohms. The recording amplifier used for the raindrop tube was one of several built for the snowmeter described in Chapter III.

One of the most difficult problems of operating the raindrop tube was smoothing the airflow so that drops could be supported in the center of the airflow away from all surfaces. Several pieces of 50-mesh brass wire gauze were used alternately in trying to smooth airflow in the tapered section for drop floating. Gauze location is indicated in Figure 2-4. Best smoothing was effected by the further addition of a grid work of three-inch rectangular brass tubes about 0.5x0.5 inch in cross section situated below the curved gauze. Further slight smoothing was achieved by judicious placement of small pieces of masking tape on bottom side of both grid and mesh. It is important that grids and gauzes be cleaned of dust at frequent intervals, lest the flow be distorted. The airflow was made sufficiently smooth to float drops for more than half an hour.

*For the record it is worth noting that considerable trouble was experienced with the contacts in this switch.

Raindrop Tube Results

By the free-fall method described in the paragraph in the middle of Page 2-3 of this chapter, some 2,000 drops having a diameter of approximately 0.4 centimeter were disrupted, in approximately 75 runs of from 15 to 65 drops per run, the average run being about 35 drops.

The magnitudes of electrification produced by breaking drops under apparently identical circumstances vary greatly. For example, in one 50-drop run, the average deviation from the average value of charge produced was 78 percent of the average value. Such a result is typical. In order to obtain significant results, therefore, it was necessary to disrupt many drops under apparently identical conditions in order to obtain an average which had meaning.

The maximum charge produced by an individual drop broken by the technique referred to was about 500×10^{-12} coulombs (or 125×10^{-12} coulombs for that portion of the electrification measured at a single position of the electrode); while the minimum charge produced was apparently zero, that is, less than 10^{-13} coulombs per drop, which was approximately the least count in charge sensitivity of the system. Strangely enough, the charge commonly was zero. All experiments (except those referred to in a following section on supercooled water) were conducted in the neighborhood of 23° Celsius at atmospheric pressure. A portion of one record is illustrated in Figure 4-9 , which shows six drops and a calibration. Three drops yielded large charges, two yielded small charges, and one yielded zero. Some runs show more frequent and larger charges. A portion of the record for one drop appears spurious since it does not show the typical decay. Such an event occurred occasionally, probably when a highly charged fragment came near the electrode but did not strike it.

The experimental procedure was such that a determination could be made of the size of the electrified particles by measuring their mobility or speed in unit electric field. The measurements were restricted to mobilities greater

than 0.25 centimeters per second per volt per centimeter because of various limitations on experimental equipment. For example, the limiting value of high voltage was about 12,500 volts.

For particles substantially larger than normal ions in air, the mobility k is related to the particle diameter by a very simple expression $k = 76 \times 10^{-16}/s^2$ where s is the sum of the radii of a molecule in air and the particle (ref. 7). For all practical purposes in the mobility range lower than about 0.5, s is equivalent to the radius of the particle. The simple theory leading to this equation does not apply with precision to mobilities greater than about 0.5, and in fact even the most involved mobility theories are inadequate to define precisely the nature of normal ions in air, which have a mobility of approximately -2.2 or +1.8 cm/sec per volt/cm.

For the type of apparatus used, the mobility can be calculated simply from the following relation

$$k = vd/LE$$

where v is the velocity of the air blast in the open square section of the wind tunnel; in all the experiments reported here v was 865 cm/sec. (Therefore at the bottom of the 4x4 inch section of the wind tunnel, the speed was 1730 cm/sec, and at the top of the tapered section it had been reduced to 865 cm/sec, which is what it was everywhere in the 4x8 inch section, see Figure 2-4.)

d is the average distance the charged particles travel across the tube, or in these experiments, 6 inches or 15 centimeters, since the midpoint of the outlet of the tapered section is only 6 inches transversely from the electrodes.

L is the distance downstream (vertically upwards) to the center of the collecting electrode from the point where the two wind tunnels join at the top of the tapered section.

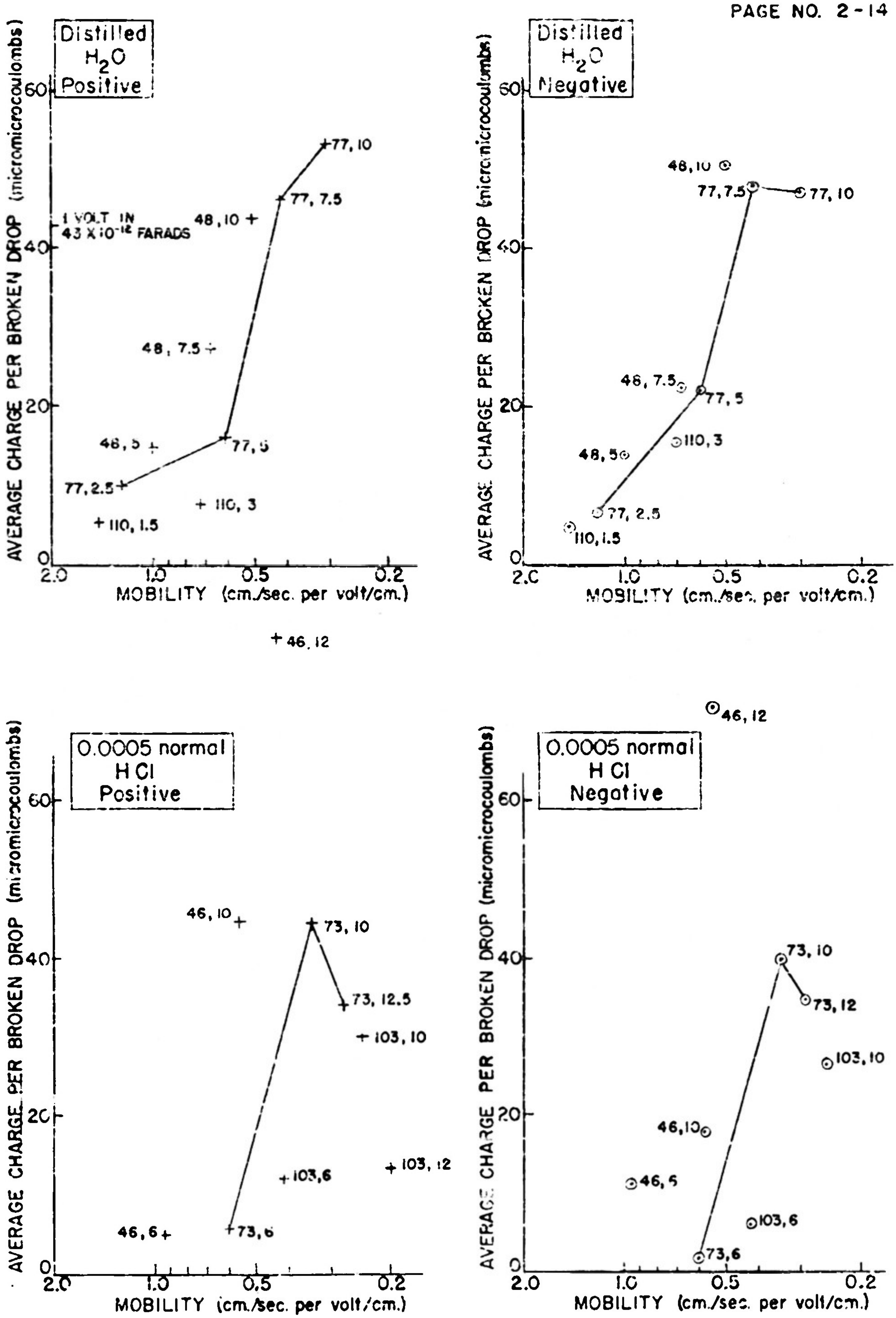
E is the electric field in the measuring section, $E = V/w$, where

V is the potential difference between the plates, (values ranged from 1,000 to 12,500 volts), and

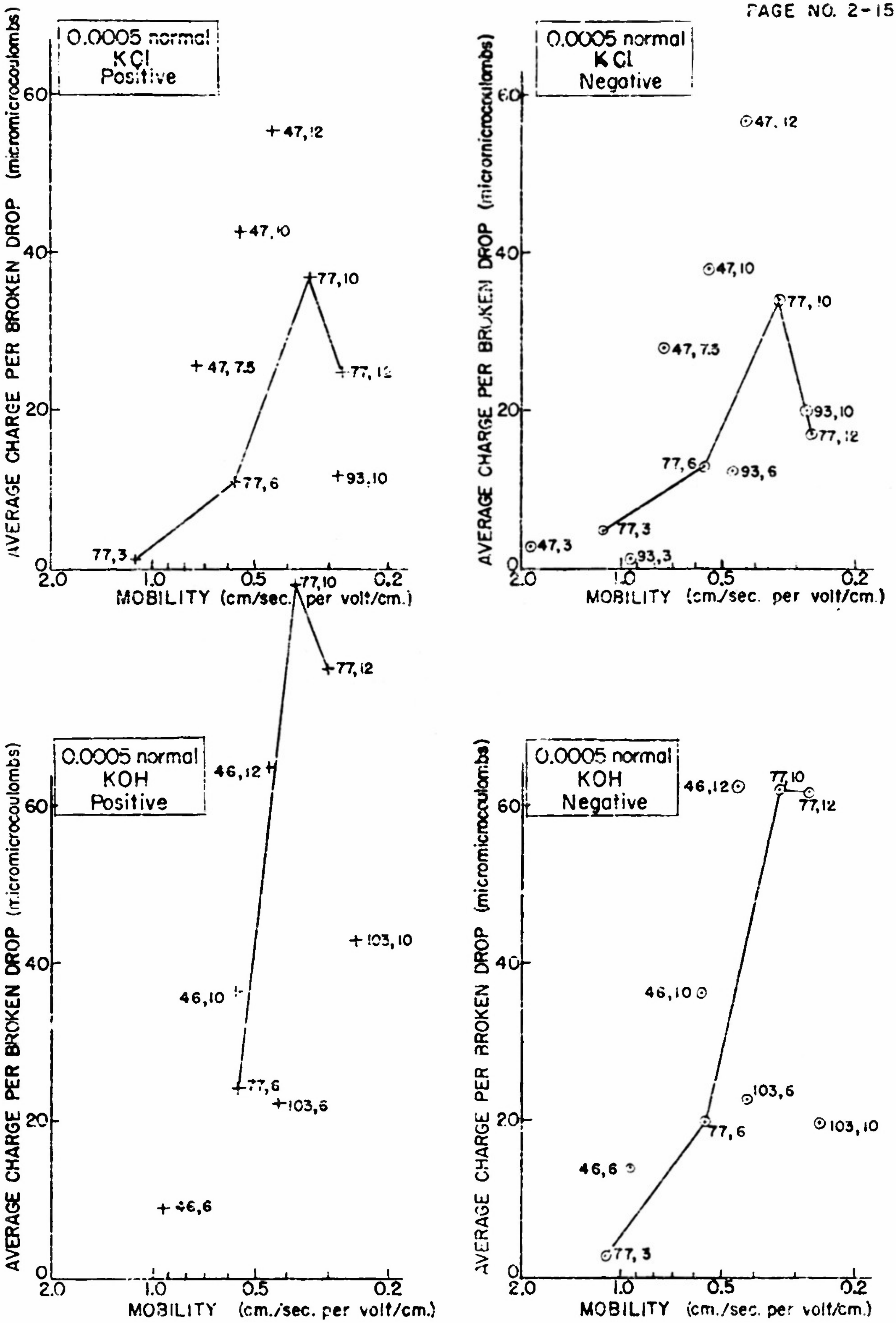
w is the distance between the high voltage plate and the electrodes, 8 inches or 20 centimeters.

Since it is easily demonstrated that the geometry of the particular tube is such as to provide only limited resolution in mobilities (although that was all that was wanted in this case) fringing effects of electric fields have been neglected. The restriction to mobilities greater than 0.25 cm/sec per volt/cm is not a serious one in thundercloud electrification theories, since it is only the high mobility ions having mobilities greater than about this value which can be effective in thundercloud electrification.

Experiments were conducted on distilled water (supplied commercially in five gallon bottles), 5×10^{-4} normal hydrochloric acid, 5×10^{-4} normal potassium hydroxide, and 5×10^{-4} normal potassium chloride. Separate results for positive and negative electrification are shown on the following pages, 2-14 and 2-15, where the ordinate is the average charge per broken drop, or to be more precise operationally, the voltage produced in the electrode capacitance of 43 micromicrofarads. The abscissa is the mobility in centimeters per second per volt per centimeter, plotted on a logarithmic scale. It is shown in Ref. 7 that by plotting mobility on a logarithmic scale the area under the charge versus mobility distribution curve corresponds to total charge, a result which would not be true for a linear plot. Each point on the graphs corresponds to a run of from 15 to 65 drops and plots the average charge per drop for the run. The first number attached to the point, for example 77, means that this run was made with the center of the electrode 77 centimeters from the inlet. The second number attached to each point, for example 5, means that this run was made with the potential of 5 kilovolts across the tube. The mobilities represented by various selections of electrode distances and potential differences is not very orderly, and it is regretted that the investigation was not more systematic. The greatest range of mobility seems to have been



RAINDROP TUBE RESULTS
FIGURE 2-14



RAINDROP TUBE RESULTS
FIGURE 2-15

covered when the electrode was about 77 centimeters downstream, and the points representing these runs have been connected by lines. The magnitudes of charge for different electrode distances differ from one another since the electrode subtends different solid angles at the inlet for different distances downstream. Had a single series of mobility measurements been made at one electrode distance, then the area under the curve would represent the total charge for the mobility range covered. The assortment of electrode distances was somewhat irregular, however, and to obtain estimates of total charge produced (that is, charge in all mobility ranges), the following procedure was used. While it is not perfectly rigorous, the variations from drop to drop are so great that complex techniques seem unwarranted, and it is felt that the computed values correspond realistically to the desired quantities.

The sum of the average charge per broken drop for all points in a given graph has been divided by the total number of drops. This grand average has then been multiplied by a factor of 4, which is the reciprocal of the fraction of the high mobility particles in the range from $k = 0.25$ to $k = 1.4$ sampled by the electrode. For example, when the electrode is 77 cm from the inlet, it intercepts particles that reach the grounded side between 62 and 92 cm. With 7.5 kilovolts on the tube, the limiting mobilities are 0.38 and 0.5. On the logarithmic scale this range corresponds to 1/4 of the total mobility range covered. If all the curves had covered the same mobility range, one could have used a planimeter to measure area under the curves. Actually corresponding curves made at different electrode distances, are not mutually consistent in magnitudes within a factor of 25 percent or so--which is not surprising in view of the highly random nature of the drop-breaking situation--and this approximate method is probably as good as any. The limitation at the high mobility end of the range probably is not too serious; if great quantities of ions of mobility about 2 cm/sec per volt/cm had been generated, some of them should have reached the electrode centered at $k = 1.4$. The values are shown in the table:

Total Charge, coulombs per broken drop from k = 0.25 to k = 1.4

	Positive	Negative
Distilled water	$+100\times10^{-12}$	-104×10^{-12}
5×10^{-4}n HCl	$+120\times10^{-12}$	-100×10^{-12}
5×10^{-4}n KOH	$+184\times10^{-12}$	-148×10^{-12}
5×10^{-4}n KCl	$+112\times10^{-12}$	-108×10^{-12}

It had been hoped to cover a range of concentrations from 10^{-5} molal to 10^{-3} molal, since it is in this concentration range that the influence of the electrolytic ions in solution have the greatest influence on surface phenomena (ref. 7) for instance in electrification on breaking of drops. Unfortunately time and funds did not permit this program to be covered to the extent hoped, and it is regrettable that since the whole range could not be covered, the concentration chosen should not have been nearer to the center of the desired range. In general, one expects acids, bases, and salts to increase electrification over that for distilled water up to a concentration of about 10^{-3} molal, when it begins to decline again.

An important result is clear: that positive and negative electrifications are approximately equal in the high mobility range. While this result is in agreement with our earlier work (refs. 4, 6, and 7), it is contrary to the historical opinion of the breaking-drop theory of electrification, which presumes that only negative charge is found in the air.

The magnitudes (about 100×10^{-12} coulombs per drop on the average) should not be given too inviolable a position. One can vary the magnitude of charge over wide ranges, one or two orders of magnitude, but generally only towards smaller magnitudes, by changing the method of disruption.

When a large drop is allowed to float for some minutes in the vertical wind tunnel with smooth airflow, and then another drop is introduced, after a while the two will chance to come together. Sometimes the result is merely the formation of a larger drop; sometimes, the combination disrupts and

shatters so that all fragments are blown away; and sometimes the "combined drop" has a volume less than the sum of the volumes of the components, commonly much less, and parts of the drop are blown away. In smooth coalescence there really is no source of energy to overcome surface tension forces, and it is reasonable to assume that large numbers of small droplets are not formed. In the coalescence experiments it appears to the eye that the drop is not really shattered, but more nearly broken into several visible or large fragments, probably with some but not many microscopic particles. In no case is the electrification ever very great, and ordinarily it is zero (less than 10^{-13} coulombs/drop).

One must conclude that calm, smooth coalescence of drops followed by disruption into large fragments cannot possibly be significant in thundercloud electrification. On the other hand in the method described earlier in this chapter, where the drop falls freely for 5 centimeters or so before encountering the updraft, and from which it acquires a velocity of about 1 meter per second against the vertical updraft of 8.65 meters per second, which is followed by its disruption into microscopic particles, the electrification is considerable (commonly 100×10^{-12} coulombs/drop). There is a rough correlation between magnitude of charge recorded, and the apparent completeness of disruption as judged by someone watching the process, where one drop is disrupted about every 25 seconds. With practice, a man can estimate the magnitude recorded with qualitative accuracy more often than not, but there is no simple objective method of estimating the completeness of disruption.

The author does not know whether the microturbulence structure of thunderclouds is well known or not; that is, turbulence on a scale of inches or a few feet, but from observations he has made of snowflakes seen out his back window at night with the aid of a bright spot-light, he is under the impression that even in rather mildly turbulent air, there is a great deal of microturbulence.

Aerodynamic theory implies that lift cannot exist on airfoils (or anything else for that matter) unless there is circulation about the object. The showery nature of most thunderstorm precipitation implies a lift on the precipitation at times which distorts its rate from uniform to irregular even over intervals of one second.

Hence, it seems reasonable to assume that there is considerable micro-turbulence in thunderstorms which can introduce transients in relative motion of drop and air of 1 meter per second, or a free fall distance of 5 cm, especially if two drops agglomerate so they would have a terminal speed greater than that of the individual components.

If that assumption is true then it is critical in a thundercloud electrification theory to determine whether 100×10^{-12} coulombs per broken drop is of a magnitude which may be sufficient to account for (a part of) the thundercloud electrification. We may proceed as discussed in the next section.

Breaking-Drop Random-Collision Electrification Theory

To calculate the effective average charging current in a thunderstorm associated with the breaking drop electrification process, we may proceed as follows:

Let I = the average charging current

Q = total charge generated in time t

t = time

q = average charge per broken drop

N = total number of raindrops in the thunderstorm

V = volume of thunderstorm

n = number of drops per unit volume

λ = the effective mean path of drops in thunderstorm between collisions in turbulent air

v = average random velocity of drops relative to each other in turbulent region

S = average diameter of raindrops

W = weight of liquid water in raindrops per unit volume of storm

D = density of water (1,000 kilograms per cubic meter).

As referred to above, let us make the assumption that in the turbulent region of the thunderstorm of volume V the raindrops are moving in such a way that we may consider their motion to be random at an average velocity of v relative to each other. Then by analogy, the collision of raindrops may be investigated by means used for collisions of molecules in the kinetic theory of gases. Let us further assume that when two raindrops collide, it is their collision which results in the necessary additional velocity of the raindrop relative to the turbulent air to cause its disruption. Then the average time t between disruptions for any one drop is

$$t = \lambda/v$$

At some stage in the analysis it will be necessary to introduce a factor of 2 since there is only one collision per 2 drops. Since current is charge per unit time,

$$I = q/t = q\ N/2\ t$$

or $$I = \frac{qnV}{2\lambda/v}$$

but $\lambda = 1/(\sqrt{2}\ \pi\ S^2 n)$ (see any book on kinetic theory of gases).

Thus $I = q\ n\ V\ v\ \pi\ S^2 n/\sqrt{2}$

or $I = q\ V\ v\ n^2\ S^2\ \pi/\sqrt{2}$

Now the volume of one drop is $\pi\ S^3/6$ and its weight is $\pi\ S^3\ D/6$.

Hence $W = n\ \pi\ S^3\ D/6$

or $n = 6\ W/(\pi\ S^3 D)$

Substituting for n in the last expression for I

$$I = \frac{36}{\pi\sqrt{2}}\ \frac{qVvW^2}{D^2\ S^4}$$

or using the value for the weight density of water (1000 kg/m^3)

$$I = 8.1\text{x}10^{-6}\ qVvW^2/S^4 \qquad \text{(equation 2-21)}$$

in meter-kilogram-second units. (Exactly the same value for the current in amperes is obtained, of course, with any consistent set of units, whether they be MKS or cgs, or whatever you choose.)

As an illustration consider $q = 100\text{x}10^{-12}$ coulombs/drop, $V = 10\text{x}10^9$ meter^3 or ten cubic kilometers, $v = 4.4$ meters/second, $W = 0.005$ kilograms/meter^3 (or 5 grams/m^3), and $S = 0.004$ meters (or 4mm). Then $I = 3.5$ amperes, which is a value fortuitously close to the typical rates, thus if a thunderstorm discharges one 25-coulomb flash every ten seconds its average charging rate is 2.5 amperes.

We need to comment on the values selected in the illustration. The value of q is probably high, since it is easy, in the very smooth air of the wind tunnel to get values much lower. (In the next section it will be seen that smaller drops gave $6\text{x}10^{-12}$ coulombs per broken drop. On the basis of this last figure the author concluded in the abstract "Spray Electrification of Supercooled Water Drops in Relation to Thundercloud Theories," Bulletin American Meteorological Society 33, 175 (1952) that "magnitudes of charge developed by rather violently disrupted water drops are large enough to account for only a minor part of thundercloud electrification". If $6\text{x}10^{-12}$ coulombs per drop is the figure actually appropriate to this discussion of conditions inside thunderclouds, then this conclusion still stands. On the other hand if $100\text{x}10^{-12}$ coulombs is taken, then that conclusion is not necessarily correct.)

The volume V of ten cubic kilometers might be considered to be a region about 1.4 miles square and 1.25 miles high, which is a conservatively small volume for the active region of a thundercloud. The raindrop weight W of 5 grams/meter^3 may not seem so conservative, but it corresponds to a depth of water equal to 1.0 centimeter of precipitation in the 2 kilometer height of

the cloud, certainly not an unusual amount of water for the active part of the cloud. The effect is proportional to the square of W.

The value of v is more uncertain. The terminal speed of raindrops 4mm in diameter is given as 8.8m/sec by Gunn (ref. 16b) and it seems reasonable, on the basis of the random turbulence proposed above, that relative to any particular frame of reference in the air, the drops would be likely to have speeds of about half this value, since their speed could not exceed 8.8m/sec, nor could it be less than zero. This assumption is a very loose one and is one of the shaky points of the theory. Actually this velocity is used to calculate the time between impacts of drops leading to their disruption, and it turns out to be 21 seconds (free path of 94 meters and speed of 4.4m/sec). No attention is paid here to a distribution of raindrop sizes, or speeds, or to Bernoulli effects, the assertion is merely that 21 seconds seems to be a reasonable order of magnitude of time between disruptions of a drop (into say two main fragments and the uniting of the fragments with other fragments to form another drop and to disrupt again).

Finally, of course, the current depends inversely on the fourth power of S. If drops are chosen as 3mm diameter instead of 4mm, the charging rate is increased a little over three times.

Of course the theory is incomplete unless a mechanism is postulated for separating the charge once it is generated. This mechanism must also yield the correct polarity.

Imagine the insides of the turbulent part of the cloud, with a mixture of raindrops and high mobility ions <u>of both signs</u> generated by the spray process and by the separation of polarization charges induced on the drops by the electric field when these drops are broken. Imagine that initially the potential gradient is typical of fair weather. Then in a manner similar to the classical Wilson induction mechanism, the raindrops are polarized with positive charges on their lower faces, negative charges on their upper faces. In general, the ions of both signs tend to be blown upward in the

updraft (with negative ions somewhat accelerated by the field and positive ions retarded, so as to tend to neutralize it). The negative ions are captured preferentially on the heavier raindrops moving down relative to the air in the updraft, although they are more nearly stationary relative to the ground. The positive ions are preferentially blown farther upwards. Thus, in the region where these charge generation processes are effective, the copious supply of broken-drop-generated ions of both signs provide the charges which are separated mechanically, and by polarization.

The ideas suggested here are fundamentally different from those of Wilson in that he presumed normal atmospheric ionization would provide sufficient electrification. Even with entrainment of large quantities of outside air into a thundercloud it is easy to show that the ionization would be totally inadequate. In fact for the normal ionization (1000 ion-pairs per cubic centimeter) to be sufficient, the entire air within the storm would have to be replaced once every 2.5 seconds to equal the charge provided on the basis of these calculations of breaking drop electrification. Not only do these experiments indicate that a substantial amount of charge is available, but they show that both positive and negative electrification is available for separation. One need not rely as the original breaking drop theory did, on a net difference between positive and negative charge being separated with negative in air and positive on heavy drops. In this theory any net electrification on heavy drops (which incidentally would have the proper polarity) is of minor magnitude compared with ionization picked up from the air by induction capture.

The author recognizes that his description is inadequate in many respects, for example it does not account for the proximity of the lower negative charge center to the freezing isotherm, nor does it make use of any ice-process for electrification, which intuitively would seem to be very important in view of investigations of Workman (ref. 43) and Kuettner (ref. 20a), nor does it account in any quantitative way for the initiation of rapid build up of

electrical charges in five or ten minutes in a cumulus cloud which has "looked about the same" for the preceding three hours without electrical activity.

As mentioned in the later section on Recommendations, the limiting value for induced charge on spheres in an electric field is comparable with the value for electrification of broken drops in a field-free region. Clearly the build-up of charge on a polarization-breaking-separation mechanism would be a function rapidly increasing with the time (exponential) until the inhibiting influence of the field on ion migration in the updraft held positive ions nearly stationary relative to raindrops. Perhaps the rate of build-up can be explained in this way. On the other hand, some element to start the process seems to be missing in this discussion.

On the basis of the material presented here, the author contends therefore, that electrification by breaking drop processes (field-free or polarization) cannot be ruled out as a thundercloud mechanism on the basis of any alleged inability to generate the right order of magnitude of charge.

Electrification of Supercooled Water Drops*

A large fraction of the water substance in a thundercloud is in the liquid phase at temperatures colder than freezing. Because of the spectacular results achieved by Workman (ref. 45) in the electrification of rapidly freezing water, and the investigations of Kuettner (ref. 20a) it seemed possible that spray electrification of supercooled water might yield charge values

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*The work in this section, carried out largely by Mr. Haney, was supported by the Cornell Aeronautical Laboratory Internal Research Fund subsequent to formal completion of this project. The section is included in this report because of the intrinsic interest of the subject to the field of the project studies.

considerably different from those for warmer-than-melting water. For example, one might expect surface phenomena of super-cooled water to differ from those of warm water because of the instability of the surface at sub-melting temperatures.

Cold air for the raindrop tube was obtained from out-of-doors during February 1952. There was a temperature rise in the blower system of 8°C so that to obtain adequately cold air, the outside weather had to be really cold. (To avoid this temperature rise, the blower might have been installed at the outlet of the raindrop tube rather than on the inlet, but blowers already had been installed on the inlets, and were left there--we merely waited until the weather was cold enough.) Only a single blower was used in these experiments, supplying the 4x4 inch section of the raindrop tube. The other blower was left turned off. In this way, by properly positioning the electrode, essentially all the high mobility charge was collected by the electrode, and no attempt was made to determine its mobility spectrum.

It soon became apparent that it was impossible to introduce super-cooled water into the raindrop tube, for the water froze on the inlet or free-fall guard tube, mentioned on page 2-3. Therefore warm drops at about +10°C were introduced into the tube, and allowed to remain there long enough to become supercooled.

Four lines of evidence led to the conclusion that the drops were actually supercooled since, of course, their temperature could not be measured after disruption. First, some rather simple measurements were made with a thermocouple on similar drops. Second, some calculations were made (one week-end) by Dr. John Beal of the rate of temperature change of the center of a drop on the assumption that it had finite thermal conductivity, and that its surface assumed the wet-bulb temperature of the air immediately. Third, Dr. Beal calculated the rate of change of temperature of the drop on the assumption that its thermal conductivity was infinite, and that its temperature was influenced by conduction to the adjacent airstream and by evaporation. All

three arguments were in substantial agreement with each other, that the time constant for the temperature-time curve of a raindrop was of the order of 10 seconds. Fourth, though subsequent to the work of Dr. Beal, we studied the extensive analysis of Gunn and Kinzer (ref. 16c) who have considered the matter rigorously in great detail. All lines of reasoning are in agreement that the drops we used had a temperature of about -6°C at the time they were disrupted, about 20 to 30 seconds after introduction to the raindrop tube.

In a somewhat turbulent airstream, it is rather easy to disrupt a floating drop by almost any means, for example by passing a pencil or other object quickly under the drop. In our case, this method was ineffective; so also was an abrupt momentary change in the flow, achieved by slamming a board over the inlet to the blower, and allowing the board to rebound.

An effective scheme involved the placing of two 1/8 inch diameter air jets connected to the 100 pounds per square inch compressed air supply of the Laboratory (after all water had been blown out of the pipes) in such positions in holes on opposite sides of the tapered section of the raindrop tube that the blasts from them would intersect in the region where the drop was floating. An instantaneous puff of air from the jets would disrupt the drop. While the compressed air was not refrigerated, it seems highly unlikely that this momentary puff of air could affect the temperature of the drop very much, though if the experiment is repeated, it would be desirable to refrigerate the jets.

Two runs were made on drops 3 millimeters in diameter with essentially no differences other than the temperature of the drops. The results should be considered suggestive since they can hardly be considered definitive in a statistical sense for there were many experimental difficulties, and the dispersion of charges was greater than in most runs. A group of 66 drops, supercooled to an average temperature of -6°C was disrupted and yielded an average total charge of high mobility particles of $6.8 \pm 1.4 \times 10^{-12}$ coulombs per drop, while 98 drops at an average temperature of +14°C with other conditions similar, yielded nearly as much electrification, $6.3 \pm 1.2 \times 10^{-12}$ coulombs per drop.

At no time was there any evidence of freezing of the drops. It is to be noticed that the charge magnitude in this set of runs was distinctly less (by an order of magnitude) than in the case of the 5cm-free-fall drops. It is really almost impossible to assign any objective criterion for the degree to which drops are shattered. Under different circumstances we have observed charges ranging from 10^{-13} to 10^{-10} coulombs per drop.

The conclusion to be drawn here is that under conditions of these experiments, supercooling the water does not significantly affect the electrification.

Recommendations

It should be clear from the foregoing that the spray electrification process is far from understood completely, since the breaking of drops under differing circumstances results in markedly differing magnitudes of charge. It is known that the atmosphere contains great quantities of various "impurities" and that raindrops are not pure water. It would seem, therefore, that more extensive studies are warranted on solutions of various substances to determine how the electrical effects are influenced by electrolytes or other materials. Ammonium salts (ref. 43) should be particularly interesting.

The one run reported here on supercooled water appears to give negative results so to speak, on the importance of breaking drop electrification of supercooled water. It may be, however, that while warm water is influenced apparently only slightly in its electrification by the breaking drop mechanism by the addition of electrolytes, supercooled water or freezing water may be significantly influenced. Workman's investigations make it seem quite likely that a great deal more remains to be learned about supercooled water or freezing water. Unfortunately it was not possible to carry out more than the single series of measurements on supercooled water, and the one run reported here should not be considered as closing the issue.

In all experiments reported here the breaking drops were in an electric-field-free-region. No experiments have ever been reported of breaking drop electrification in the presence of a field. In a thundercloud of course,

the drops are in a region of strong electric field. Induced or polarization charges must be on the drop when it is shattered and these charges will be "liberated" in the disruption process along with surface charges found in the field-free case. For a spherical drop of 4 millimeters diameter in an electric field of 3,000 volts per centimeter which is probably the maximum field existing in the heart of a storm (typical values being perhaps 10 percent of this value although curved surfaces on aircraft may have larger fields), an elementary calculation shows that the total induced charge on one hemisphere of the drop (which is $3\varepsilon_o E_o \pi A^2$ or 3 x permittivity of space x external field x cross section area of drop) is 100×10^{-12} coulombs. Somewhat by coincidence this limiting value is exactly equal to the breaking-drop datum.

If the drop is drawn out parallel to the field on disruption, the charge will be even more. For example, for an ellipsoid with major axis parallel to the field, 8 times the length of the minor axes, the induced charge density at the tip is almost exactly $36/3 \approx 12$ times the charge for a sphere. Since the volume of a sphere is $4\pi A^3/3$ where A is the radius, and for a prolate ellipsoid the volume is $4\pi ab^2/3$ where a and b are the semi-major and semi-minor axes, when $a = 8b$, then $A = 2b$ for figures of equal volume. It can be shown by a complicated integration that for the prolate spheroid the total charged induced on the upper half ellipsoid is $36\,\varepsilon_o E_o \pi b^2$ (with the same factor of 36). Thus if a spherical raindrop were pulled out into this type of ellipsoid with the same volume, the total induced charge of one sign would increase from $3\varepsilon_o E_o \pi A^2$ or $12\varepsilon_o E_o \pi b^2$ to $36\varepsilon_o E_o \pi b^2$, an increase of about three times. While drops in a field-free region would not be shattered when they are in the simple shape of prolate ellipsoids, the drops will be in a region of strong field and they may break up with tongues of water and tiny droplets pulled out of the top surface of oblate ellipsoids (or pushed out from it by the air blast). Induced charges on such elongated sections may be considerable. Experiments investigating breaking drops in electric fields clearly should be carried out.

Certainly there are large fields in theory and experiment still available for investigation in electrification problems.

III. THE SNOWMETER INVESTIGATIONS

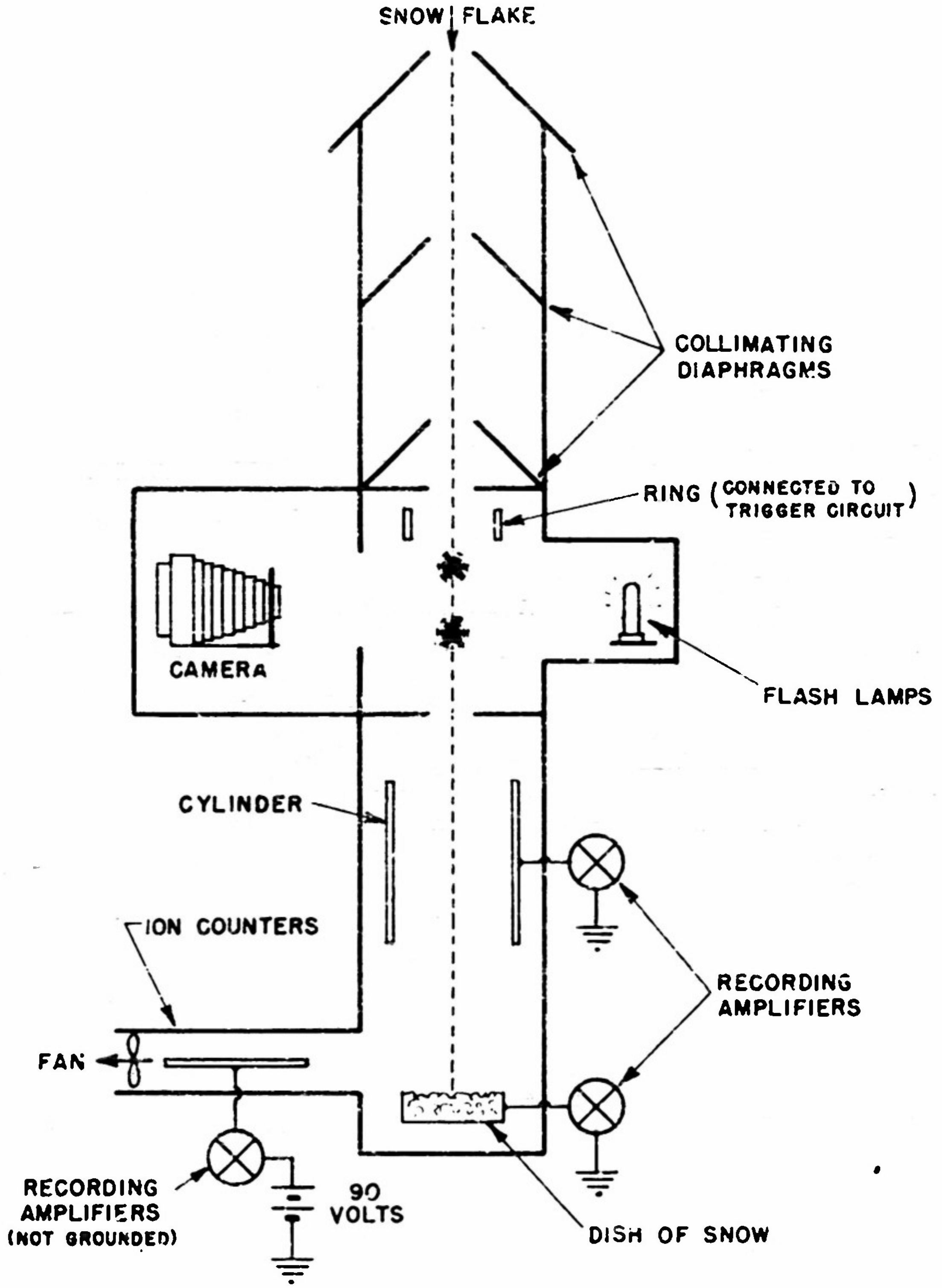
Background

It is well known that snow crystals exist in the upper parts of thunderclouds. In the literature, however, one finds very little information regarding the electrification of snowflakes. Simpson had observed charging of snow in the Antarctic in which the impact of ice crystals on one another produced a net negative charge on the ice crystals leaving the air positively charged, but significant quantitative data are lacking. A few experiments had been carried out at Stanford University (ref. 4) on electrification produced when one snowflake struck a dish of snow collected from the same storm, but the results hardly can be considered definitive.

It seemed advisable to extend the experiments on snow at Cornell Aeronautical Laboratory in Buffalo where there are plenty of snowstorms each winter with many kinds of snow. The apparatus about to be described was constructed for the purpose of conducting the snow experiments, but the experiments could not be carried out until March, and the information obtained during the March storms was not particularly significant. The snowmeter which had been used at Stanford University was received in very poor condition at Cornell Aeronautical Laboratory (many parts broken and damaged), and in any case it seemed desirable to make certain improvements in the apparatus. The decision was made, therefore, to rebuild the equipment.

Brief Description

The snowmeter, which is illustrated schematically in Figure 3-2, consists essentially of a brass cylinder 6 inches in diameter and about 3 feet long. At the top of the meter is a series of truncated cones having axial holes 1.5 inches in diameter which serve to collimate the paths of snowflakes



SNOW METER

FIGURE 3-2

admitted to the apparatus. Thus, snowflakes must be moving in a particular direction in order to get inside the snowmeter without being trapped by the collimating diaphragms.

On falling through the diaphragm at the bottom of the collimating section, the snowflake enters the "photographic section", which consists of a camera housing, two gaseous discharge flash lamps and a ring electrode. Nearly all snowflakes carry some electrical charge, and when the snowflake falls through the ring, a potential is induced on the ring. This voltage is fed to the input of the snowmeter trigger circuit (see section on Snowmeter Trigger Circuit), which triggers the photographic flash lamps (see section on Snowmeter Flash Circuit). The two lamps are controlled so as to give two flashes, one following the other by controlled time interval such as a 0.020 second. In this way one may determine the velocity of fall of a snowflake by measuring the distance it has fallen in this known time interval. Actually the camera section is arranged with two mirrors so that three images are created by each flash of the two flash lamps, a lefthand stereoscopic image, a righthand stereoscopic image, and a direct image.

As the snowflake continues to fall, it passes into a section where its charge is measured accurately by induction. Irrespective of the path of the snowflake through the snowmeter, within only a small error, it must induce a voltage on the cylinder connected to the recording amplifier, directly proportional to the charge on the snowflake. The pulse output from the cylinder is stretched by a pulse lengthening circuit (see section on Pulse Lengthener) so that the maximum voltage induced on the cylinder is recorded on a recording amplifier.

Finally, the snowflake strikes a dish of snow which has been collected from snow in the same snowstorm. The dish is connected to a second recording amplifier so that the total electrical charge on the dish is measured by the second recording amplifier. In general, the charge on the dish is found to be different from the charge on the snowflake, some charge having escaped into the air.

Adjacent to the dish are two tubes through which air is sucked by a fan for measuring the charge transferred to the air by the impact of the snowflake on the dish of snow (or at least monitoring the charge--since the measurement is not quantitatively accurate). For convenience we call these tubes ion-counters, although the name is not exactly appropriate. One of the ion-counters was connected so as to collect positively charged ions on its central electrode, and the other was connected to collect negative ions.

A measurement of a snowflake consisted, then, of essentially the following items: a stereoscopic photograph of the flake together with a measurement of its velocity since the time interval between flashes was known, a measurement of the charge carried by the snowflake, a measurement of the charge collected by the dish of snow, and finally a qualitative indication of the presence or absence of electrification in the air drawn past the dish by the fans which sucked air through the ion-counters. Thus, there were four essentially simultaneous deflections of the recording amplifiers. In general, only one of the two ion counters would register any significant electrification. The snowmeter amplifiers were calibrated by dropping balls (ball bearings) through the snowmeter which had been charged to known potentials, for example 22.5 volts.

Detailed Description

The snowmeter was mounted with tripod legs so that the snowmeter itself formed one leg of a tripod. By tilting the tripod, it was possible to accommodate snowstorms under almost any condition of wind, providing one could place the snowmeter to the leeward of some building. The Cornell Aeronautical Laboratory experiments were actually conducted in Dr. Chapman's backyard, two miles from the Laboratory. His house, garage, and porch, as well as the house of his neighbor, are so arranged that irrespective of the wind direction, it is always possible to work in the lee of the wind while still retaining

immediate access to the garage which provides shelter from the storm for personnel working out of doors. All of the recording amplifiers and other electronic equipment (15 chassis altogether, which are described in separate sections) were set up permanently in the basement where they could be turned on at a moment's notice.

A matter of particular concern with the snowmeter is the maintenance of proper insulation for the recording amplifiers. It is necessary that resistances of the order of 10^{13} ohms be maintained in all weather since the grid resistors used in the recording amplifiers are of the order of 10^{11} ohms. Actually, no serious difficulty was experienced with the polystyrene insulation for the recording amplifiers connected to the cylinder and to the dish. The ion-counters were so connected, however, that the inner electrode connected to the recording amplifier was operated at a steady potential of as much as 90 volts difference from ground, the potential difference being provided by a battery. In this case, the potential across the insulation was 90 volts. The insulation resistance could never have been maintained without a guard ring technique. With the guard ring, the 90 volts from the battery was held off by bakelite insulation. Polystyrene was used to maintain insulation between the guard ring and the center electrode of the ion counter against a potential difference of a few millivolts. In order to improve this insulation, resistors were incorporated in the insulation housing so that a few watts of power could be supplied to the resistors to maintain the temperature of the insulation somewhat higher than ambient. The system worked quite well.

Through a sliding door on the side of the snowmeter it was possible to change the dish of snow in a matter of a few seconds. Although the camera and the flash tube are shown on opposite sides of the snowmeter in the schematic Figure 3-2, in fact they were at 90° as shown in Figures 3-6 through 3-10.

Details of the probes containing the electrometer tubes associated with the recording amplifier equipment are given in Figure 3-8. The

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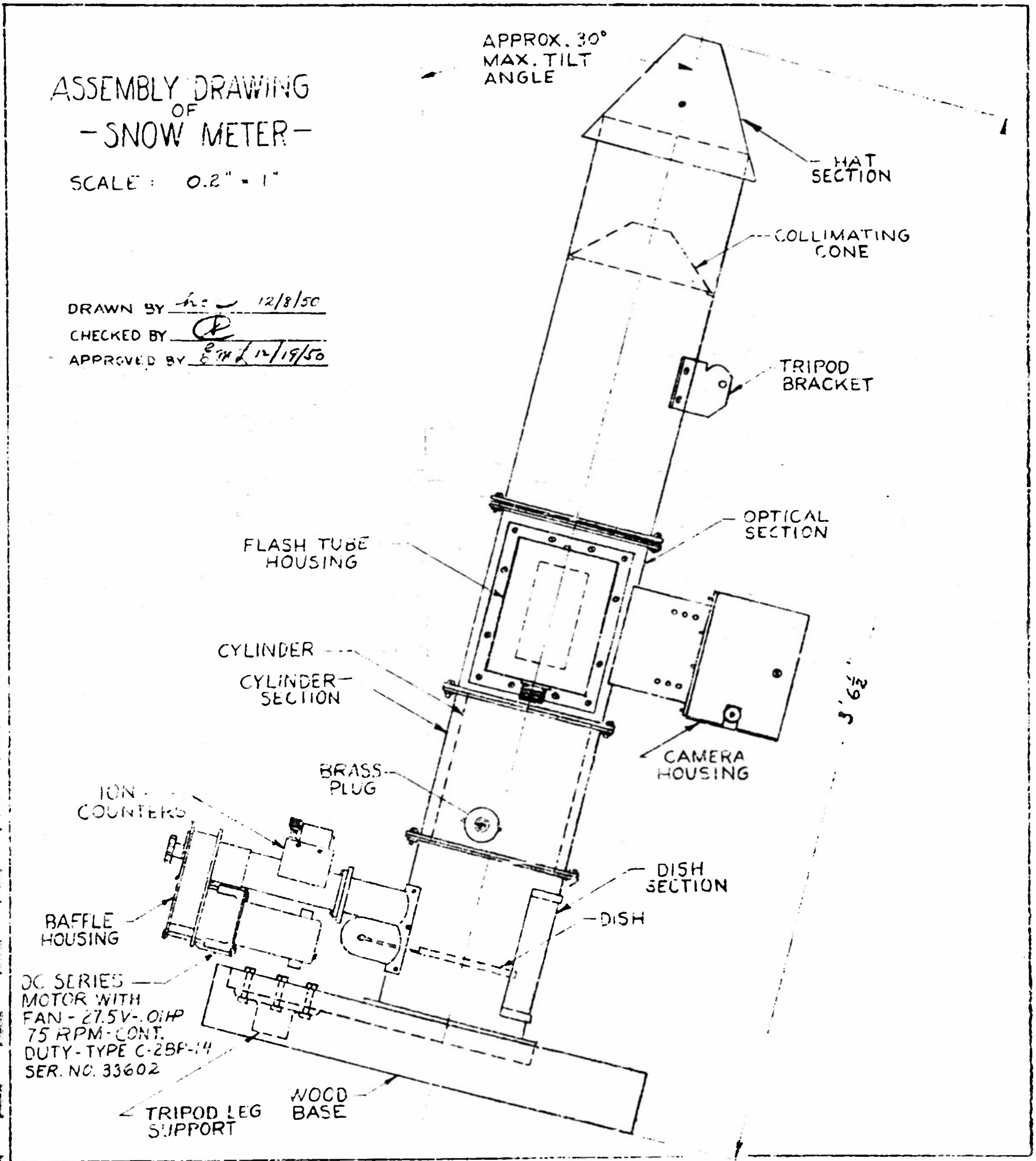

FIGURE 3-6

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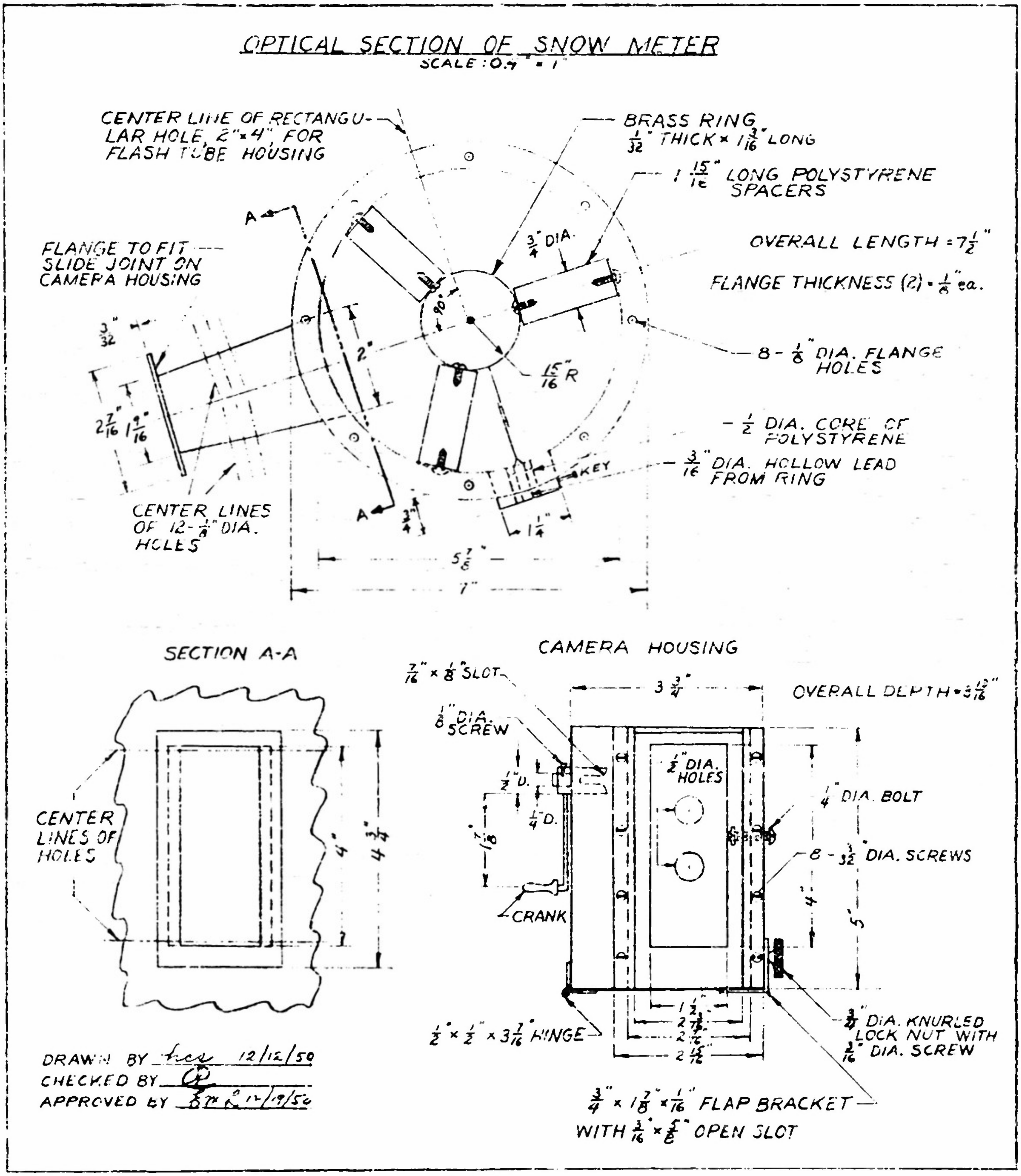
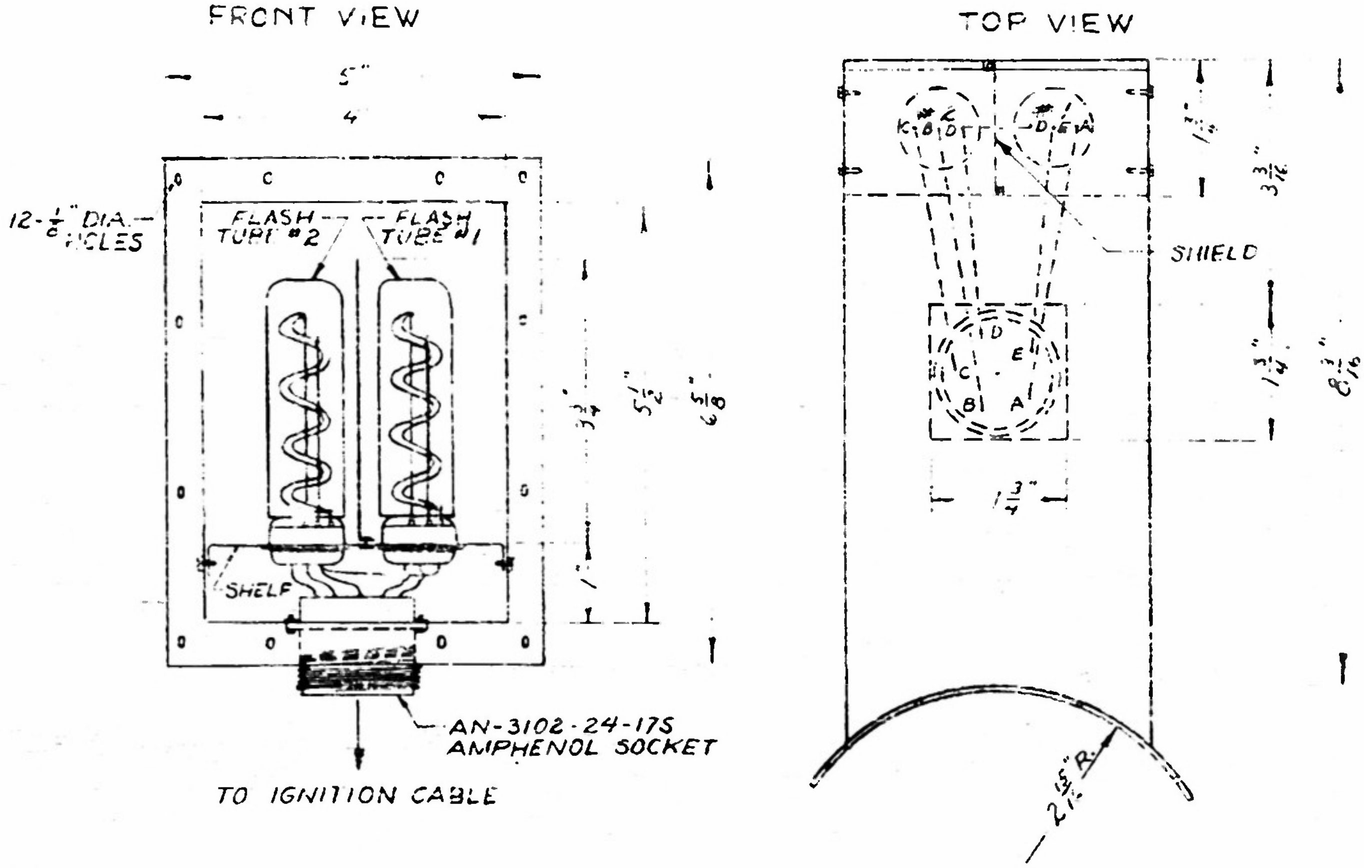
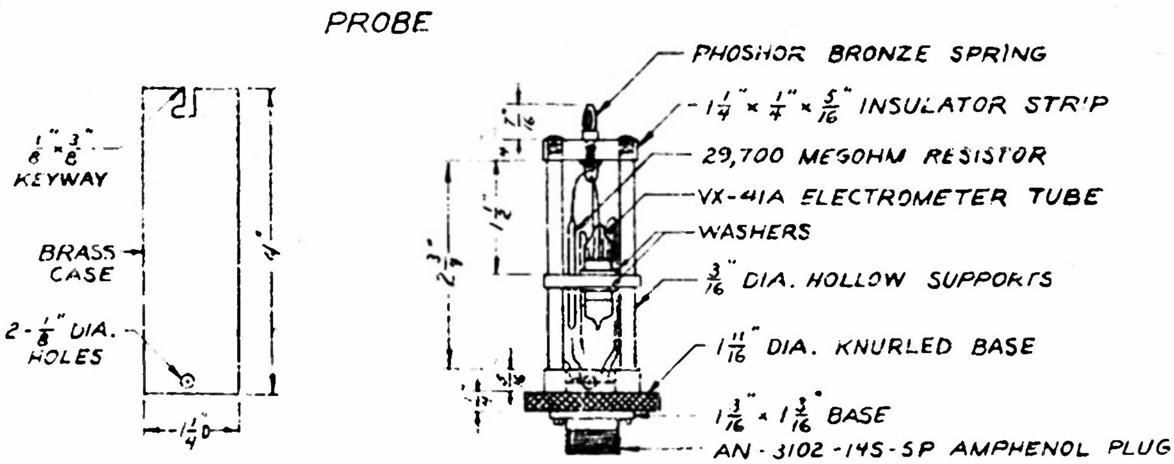


FIGURE 3-7

P-1-3750

FLASH TUBE HOUSING





DRAWN BY hcc 12/13/50
CHECKED BY
APPROVED BY 12/19/50

SCALE: 0.4" = 1"

FIGURE 3-8

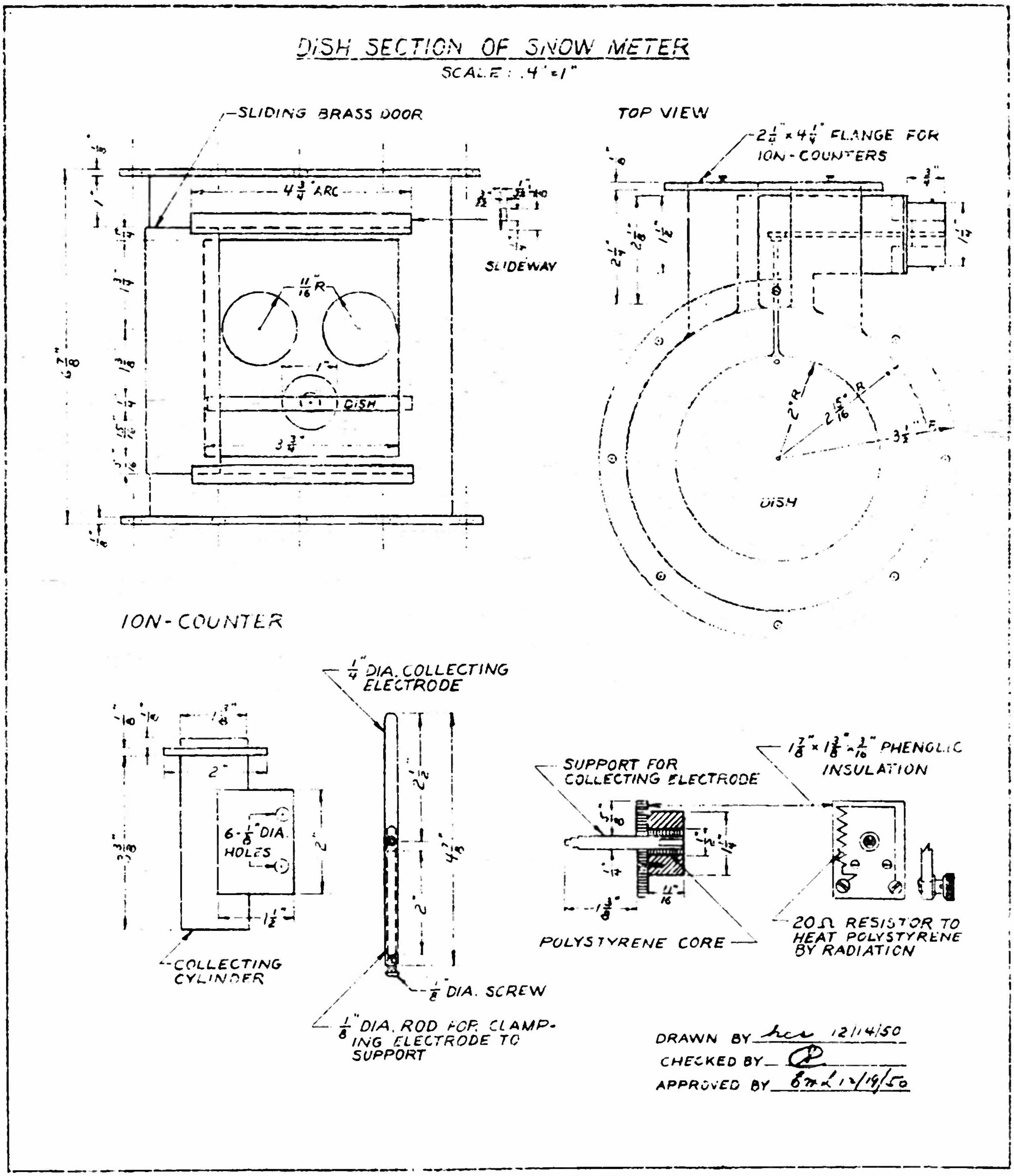
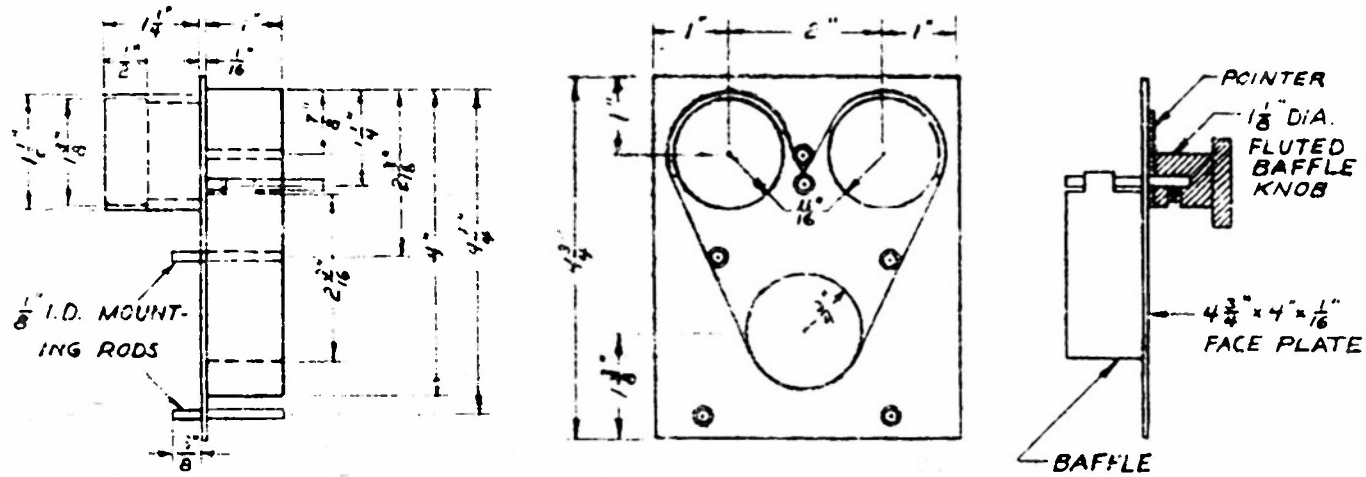


FIGURE 3-9

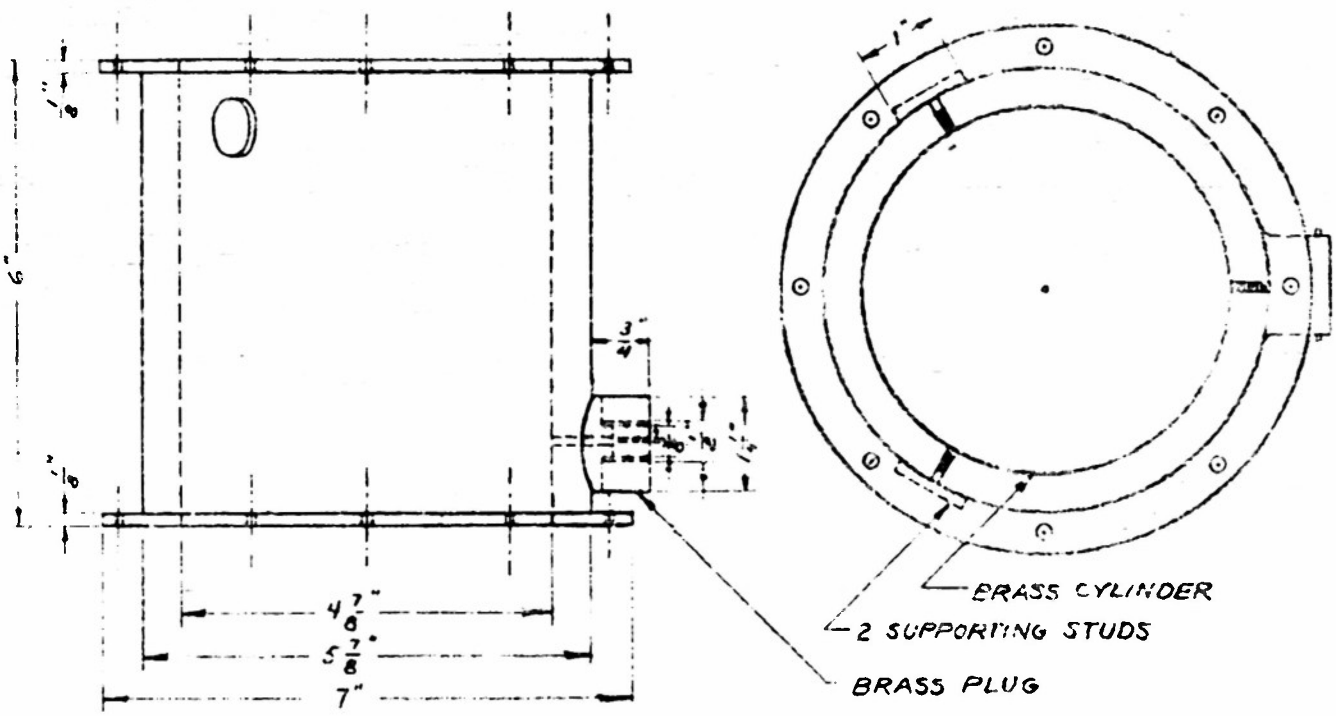
P-1-3752

MOUNTING FOR ION-COUNTERS AND MOTOR

SCALE: .4" = 1"



CYLINDER SECTION OF SNOW METER



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APPROVED BY EWL 12/19/50

FIGURE 3-10

electrometer tubes employed were Victoreen VX41A electrometer tubes. A probe contained one electrometer tube and one high megohm resistor whose resistance could be selected from about 30,000 to 300,000 megohms depending upon application. One of the probes and one of the snowmeter amplifiers were used in the raindrop-tube experiment.

Snowmeter Results

Unfortunately no objective scientific conclusions of any consequence were reached as a result of the snowmeter investigation. Work on the project had been suspended in the fall of 1949 because of financial difficulties. In February 1950 when the project became financially solvent again, a certain amount of construction work remained to be completed before the snowmeter would be ready for operation. The radiosonding equipment also had to be put into operation. Because of other Department commitments, only a limited number of scientists and technicians could be applied to this project on short notice. The snowmeter equipment became operative about the second week in March, a date close the the termination of the snow season.

After the equipment was ready, the first snowstorm which lasted longer than an hour--which is about the time required to assemble a crew and set up equipment out-of-doors--was on Monday morning, 13 March 1950 from slightly after midnight until mid-morning. Dr. Chapman set up and operated the equipment during this storm by himself, though not as efficiently as two men could have done. In view of the hour he did not feel justified in calling other members of the project crew to join him.

The storm was relatively uninteresting, however, with the precipitation consisting mostly of snow pellets of a type which do not give any significant electrification. Electrification would be expected to be prominent in the case of stellar crystals, which might have spicules that would break off on impact with the other snow crystals, for instance in the dish of snow of the snowmeter. All charges recorded on the snow pellets were of the order of

10^{-13} coulomb, a magnitude too low even to operate the photographic flash circuitry with any degree of regularity. Normal snow charges are one to two orders of magnitude greater.

The next storm of consequence occurred on Friday afternoon, 17 March 1950 from about 1530 hours until about 2100. Scientific personnel were just preparing to leave for the weekend when it became clear that this might be a "good storm". The crew donned appropriate outdoor gear, and assembled at the field station to operate the snowmeter and to make a radiosonde release. Unfortunately, during the somewhat hurried effort to get the equipment into operation, the insulation in one of the snowmeter channels became fouled, and at that moment attention was transferred to the radiosonde release, which was made later. In view of prior engagements of most members of the staff for the weekend evening most project activity terminated at approximately 1830 without snowmeter results. Dr. Chapman restored the snowmeter to operation and prepared to make a second radiosonde release with the assistance of his wife, who had previous successful experience in radiosonding. She was out with the family automobile and was expected home momentarily, but unfortunately got stalled in a snowdrift. By the time she returned the storm was clearly in its last stages. It came to an abrupt termination a few moments later some three hours before the predicted "passage" of the storm.

The next storm of any consequence occurred in April when Dr. Chapman was out of town on another assignment. By the time he returned, the snow season was definitely over.

Unfortunately, therefore, the only conclusion which can be drawn from the snowmeter effort was that the equipment was capable of successful operation.

Lightning was observed in a Buffalo snowstorm when Weather Bureau radiosondes showed temperatures at all levels to be colder than melting, but the storm was of a squally type and may have had regions of liquid drops associated with the gaining of moisture as the air crossed the as-yet-unfrozen Lake Erie.

It seems likely (ref. 4) that under most circumstances dry snow electrification cannot be of major importance in thunderclouds.

A stereoscopic photograph of a snowflake falling through the snowmeter is shown in Figure 3-14. A short portion of the snowmeter records of 13 March 1950 are shown in Figure 4-10 at the rate of 3/4 inch per minute. A portion of the simultaneous corona point record is shown in Figure 4-9 . From the corona point record it is clear that this snowstorm, electrically speaking, was very mild. On the snowmeter records, full scale deflection corresponds to 1 milliampere on the recorder, and the corresponding electrode voltage changes are indicated on the record. Several individual snowflakes (actually snow pellets) are identified by letters E, F, G, H, I, J, K. There is more noise on the cylinder record than on the dish record since the voltage sensitivity of the range used for the cylinder was greater. The zero record for the cylinder is drifting at the rate of about 0.5 millivolts per minute since the amplifiers had been turned on recently. The snowmeter pulse-lengthener was not connected to the cylinder when this record was made. Therefore the deflections for the cylinder consist of spikes rather than of step functions followed by decay, as is typical of the record for the dish.

For this particular storm, since charges were so small, the cylinder was operated on the most sensitive range, number 1, the dish on range number 3. Ordinarily ranges number 2 and 4 would be used. In calibration, a 1/4 inch diameter ball charged to 22.5 volts, would yield recorder deflections of about 0.5 milliampere on cylinder range 2 and dish range 4. The capacitance of the dish system was about 25 micromicrofarads.

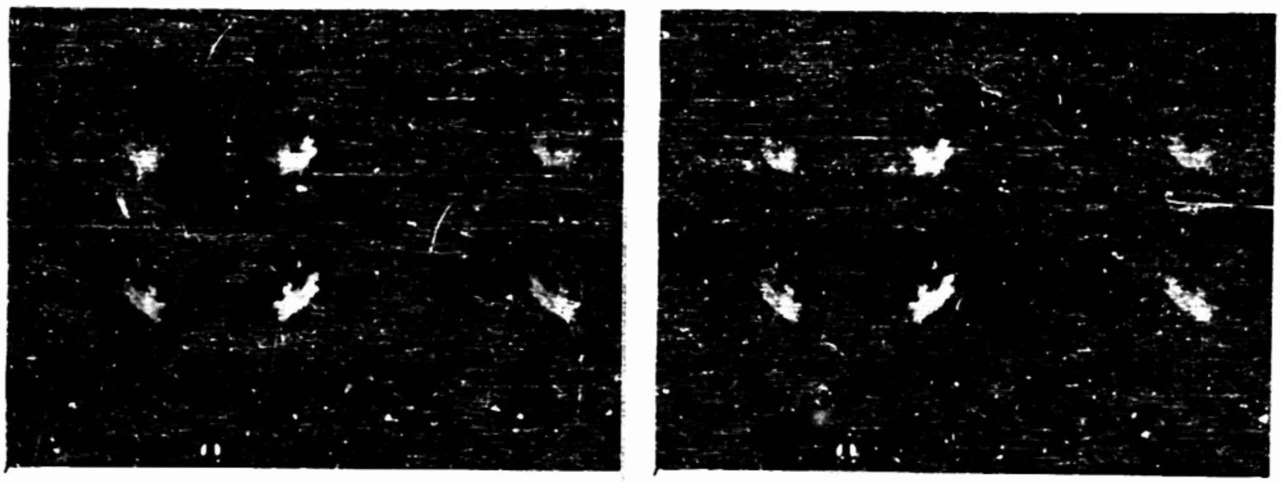
A summary of all weather phenomena referred to in this report is given on page 4-15.

CORNELL AERONAUTICAL LABORATORY, INC.

BUFFALO, N. Y.

PREPARED BY Seville Chapman REPORT NO. VC-603-P-1

Top



Bottom

Reversed Reflected Right Image (i.e. correct)	Reversed Print Direct Picture	Reversed Reflected Left Image (i.e. correct)	Duplicate Reversed Reflected Right Image (i.e. correct)	Duplicate	Duplicate
FOR RIGHT EYE		FOR LEFT EYE	FOR RIGHT EYE		

stereoscopically inverted

STEREOSCOPICALLY CORRECT I.E. LOOK AT THESE PICTURES

Note: The photographic processing requires that the negative be printed in reverse (to compensate for the reflection in the mirrors) and that the left and right images on the print be transposed so as to give the third dimension in the proper sense. There are various "tricks" for "seeing" stereoscopic pictures without stereoscopes--let it merely be stated here that those who have the knack will "see" the pictures, and those who don't have it need not bother.

Figure 3-14

SNOWFLAKE IN SNOWMETER

Recommendations

With relatively little effort, the snowmeter equipment including amplifiers, control circuitry, and associated equipment undoubtedly could be restored to operating condition. The data which it was designed to obtain still are not available in the literature. It would seem desirable to continue the experiments, providing however, that the project get under way before the snow season starts.

Many occurrences including cloud seeding nucleation and atmospheric electrification phenomena depend very critically on the detailed nature of the ice crystals or snowflakes involved. Schaefer and also Nakaya (ref. 22) have proposed a classification of snow and ice crystals of ten major types. Unless theories of atmospheric occurences take due account of the particular type of snow crystal involved, they are unlikely to make significant progress in the development of further understanding of these processes.

For an understanding of snow electrification, it seems essential, therefore, that individual snowflakes be studied. Attention to individual flakes is one of the fundamental notions in the snowmeter equipment described in this report. In this case the flakes could be photographed; in some other kinds of experiments replicas might do as well. Since significant data on snow electrification still do not exist, and since the electrification processes may be so important in many phenomena, it seems highly desirable to obtain electrification data on individual snowflakes.

IV. THE CORONA POINT INVESTIGATION

Introduction

One of the main objectives of the project discussed in this report was to investigate snow electrification, inasmuch as snow is a constituent of thunderclouds and may be important in their electrification. Snow electrification may be investigated on the basis of single snowflakes as reported in Chapter III, and some information may be gained also from investigating snow in the atmosphere by measuring the electric field created by the snowstorms.

In normal fair weather a negative electric field or positive potential gradient exists in the atmosphere of about 130 volts per meter at the ground. This situation corresponds to positive charges overhead and positive charges flowing toward the ground. (Polarity of the field has always been subject to confused terminology, even though everyone agrees on the sense of the actual normal fair weather field.)

From the literature one would get the impression that the atmospheric electric field during a snowstorm would be relatively constant with positive charges flowing toward the ground. It seemed important to set up some simple means for investigating the electric field during a snowstorm to see whether some additional information might be obtained. The results, in fact, are very remarkable. The field ordinarily changes rapidly, fluctuates considerably within a few seconds, and may reverse frequently within a minute or two. Only once (see 9 Mar 50) was the field constant in polarity, positive charges flowing toward the ground with blowing snow and then the fluctuations in current were considerable. (See Figure 4-9.)

The main reason why the behavior of the earth's electric field during snowstorms is not understood is that until quite recently satisfactory instruments for measuring the field have not been available. In the past, most fair

weather investigations in the field have been carried out by means involving some kind of long period recording electrometer having a time constant of the order of a minute, so that short period variations could not be observed even if they had been looked for. Furthermore, the matter of maintaining high megohm resistances in inclement weather was a very difficult problem. Even the generating voltmeter introduced by Gunn for other pruposes about 1930 had not reached a stage of development where it was strictly reliable during bad weather except in the hands of laboratory research specialists.

While the method of observing the earth's electric field by measuring the corona current to a sharp point exposed from a high place such as the top of a flag pole has been known for decades, the current is of the order of a microampere, which is inadequate to operate a recording meter directly. With modern electronic techniques, however, the current can be amplified to actuate a recording galvanometer. The current between the point and the ground is a function of the geometrical position of the point (mainly its height above ground), the radius of curvature of the point, atmospheric pressure (and to some extent some other variables), and the electric field that would exist in the atmosphere near the point if the point and its support were not there. The mechanism of operation of corona point is that the electric field in the vicinity of the point is markedly distorted and concentrated by the point, so that ionization by collision occurs close to the point and produces the corona discharge. Consequently, by measuring the current to a calibrated point, one can determine the electric field in a rough quantitative sense. The measurements are accurately quantitative, however, providing the geometry is known precisely and the point is new.

The corona point suffers from several defects. The corona current is proportional roughly to the square of the field, so that if a field ratio of say 100, is to be measured, a very wide range of current, 10,000 to 1, must be handled. The corona current measurement is only semi-quantitative and it has a limited range. Unless the point is set up on a tower 200 or 300 feet high it will not give a corona current in fair weather when the field is

normal. The corona point will begin to record when the field gets to be about 5 or 10 times normal, depending upon how high above the ground the point is located. What is needed is an instrument that will record with an instrumental indication of several least counts in fair weather, and also will cover the range up to the strongest fields that may be expected in a storm, which at the ground are of the order of 100 times the normal field*. Nevertheless, the corona point method of measuring the field has advantages of simplicity and convenience, and has been used both on this project and elsewhere. Further details on corona point measurements are given on pages 8.7 through 8.10 of the Stanford Report (ref. 4), and also in this report in the chapter on Radiosonding.

Corona Point Instrumentation

Two corona points were used in these investigations, one mounted on the top of the 54 foot flag pole at Building 2 of Cornell Aeronautical Laboratory, and one mounted at the top of a 32 foot pole on Dr. Chapman's garage (2343 Kensington Avenue, Buffalo, N. Y.) approximately 1.7 miles away WNW. Details of construction are shown in Figure 4-4. Calibration of the C.A.L. corona point, which is simply spaced geometrically relative to adjacent buildings, indicates a minimum current of 0.1 microampere at a field of 500 volts per meter. The 2343 point, though lower, has complicated field distortion because of adjacent houses, etc., and appears to give a minimum indication at the same strength. A calibration for the 2343 point based on these assumptions is given in Figure 4-9, and also in table on page 4-5.

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*Cornell Aeronautical Laboratory now has such an equipment in operation.

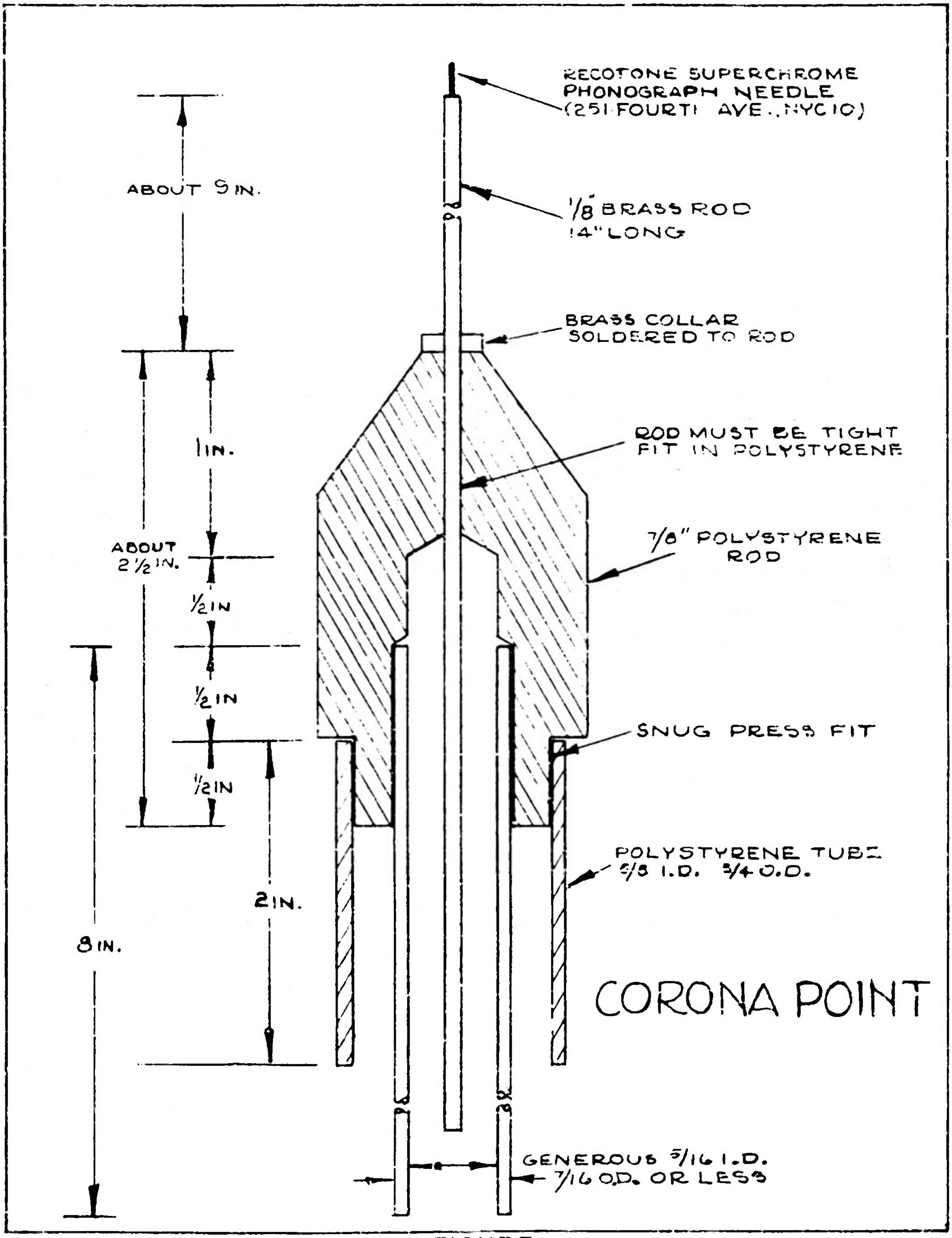
RECOTONE SUPERCHROME PHONOGRAPH NEEDLE (251 FOURTH AVE., NYC 10)
ABOUT 9 IN.
1/8" BRASS ROD 14" LONG
BRASS COLLAR SOLDERED TO ROD
1 IN.
ROD MUST BE TIGHT FIT IN POLYSTYRENE
ABOUT 2 1/2 IN.
7/8" POLYSTYRENE ROD
1/2 IN
1/2 IN
SNUG PRESS FIT
1/2 IN
POLYSTYRENE TUBE 5/8 I.D. 3/4 O.D.
2 IN.
8 IN.
CORONA POINT
GENEROUS 5/16 I.D. 7/16 O.D. OR LESS

FIGURE 4-4

Corona Current Calibration

Corona Micro-amps	Recorder Milliamps	Corona Micro-amps	Recorder Milliamps	Field volts/meter
0	0	0	0	490
+0.1	+0.005	-0.1	0.005	500
+0.3	+0.02	-0.3	0.02	540
+1.0	+0.06	-1.0	0.06	640
+3.0	+0.21	-3.0	-0.17	850
+10	+0.41	-10	-0.34	1,320
+30	+0.49	-30	-0.45	2,050
+100	+0.565	-100	-0.61	3,750
+300	+0.75	-300	-0.80	6,600
+1000	+1.08	-1000	-0.99	12,000

The recording amplifiers used for the corona point are discussed in Chapter VI. The amplifier, Model 1, was used at the Laboratory until June 1950 when it was replaced by the bipolar logarithmic amplifier. Since the Esterline Angus recording meter was connected to an output of low impedance, the meter was greatly overdamped, so that the meter did not follow rapid changes completely. In some cases the lag behind slow changes may have been a minute. The amplifier, Model 3, was used at Dr. Chapman's house. It had an output circuit designed for nearly critical damping of the output meter and reached "full deflection" within one second. The bipolar logarithmic amplifier built in June 1950 was the last and best of the group. It was somewhat more sensitive than any of the others, considerably more linear on a logarithmic scale, and had excellent output characteristics. Data were obtained from March 1949 to December 1950, including January to December 1950 when both points were operating simultaneously.

Results

From the months of corona point records which were made, five characteristics stand out:

1) Most of time, probably more than 90 percent of the time, the corona current is zero. This fact means that in most situations the earth's electric field is not sufficiently strong to generate a corona current to a point exposed at the elevation of only a few dozen feet. In fact, as explained elsewhere, the earth's field had to reach a value of about five times normal before a minimum indication (0.1 microampere) was observed with our corona points. (Smaller currents than 0.1 microampere are easy to measure, but the corona current itself is unstable below this value.) Even in severe storms the corona current to our points never exceeded 30 microamperes, which corresponds approximately to twenty times the normal field provided one assumes the correctness of the corona point calibration, a subject which is discussed elsewhere in this report in the section on radiosonding. The electric field at the ground was very weak in all cases observed in these records in comparison with fields observed in thunderclouds.

2) Under many circumstances, especially when precipitation is falling, the electric field fluctuates markedly over an interval of as little as five seconds. For instance, a visual observation of a snowstorm may show no apparent change even when the electric field goes from approximately -10 times normal to +10 times normal within an interval of sixty seconds. (See record of 22 February 1950 at 2249 hours expanded to 1.5 inches per minute in Figure 4-9.)

3) Disturbed conditions appear to have definite "signatures" on the corona records. Thunderstorms, for example, are characterized by instantaneous field charges when there are lightning discharges. The magnitude of the charge and its polarity depending upon the storm and its distance from the station. A thunderstorm record is shown in Figure 4-10. Rain and snow precipitation situations as indicated in point 2, are characterized by very rapid fluctuations in field. Disturbed field conditions can exist, however, without precipitation at the ground. Even in otherwise clear weather blowing snow at the ground can produce significant effects.

4) On many occasions over a short interval like twenty minutes, there is a pronounced time-asymmetry in the record. Examples are illustrated in the records of 9 February 1950 and 13 March 1950 at about 1600 hours. It is apparent that asymmetrical records can be produced only if substantial cloud modifications occur directly over the station or if there are horizontal inhomogeneities in the electrical structure of the cloud. The former possibility is easily ruled out on the basis of the high frequency of occurrence of the situations.

5) There is a remarkable coherence in the records of the two corona points approximately 1.7 miles apart. Time synchronization between recorders was good to about ±45 seconds in cases reported here. Usually the synchronization was accomplished by the author, either in coming to work or in going home, when he would place marks on the charts, timed against his watch within 15 minutes of each other. Many times coherent changes were observed within one minute of each other. See table on page 4-14of Corona Time Records for a few typical examples. Records at Dr. Chapman's house are marked 2343. The expected time difference: (2343-C.A.L.) is given in the last column on the basis of correction for surface wind. The actual difference: (2343-C.A.L.) is given in the next to last column.

Even allowing for the fact that the C.A.L. recorder was overdamped, it is seen that electrical effects at both stations were much more nearly simultaneous than would be expected on the basis of wind speed. One may conclude therefore that the causative agents had dimensions large compared to the 1.7 miles separation of the two stations. How these fields could change so rapidly and yet should involve dimensions of miles is not known.

Several corona point records selected from dozens that are available, are shown in Figures 4-9 and 4-10 and are summarized below. It is to be emphasized that most of these records are typical although a few show unusual situations.

Recommendations

Several problems remain to be solved. The earth's electric field measurements should be made with instruments quantitatively more adequate than a corona point from a network of a few stations. Cornell Aeronautical Laboratory (under Air Force sponsorship) presently has in operation one all-weather field meter capable of recording surface fields from about 0.1 to 1,000 volts per centimeter. We hope to make progress in the explanation, understanding, and possible application of these remarkable field changes.

*   *   *   *   *

A synopsis of all-weather situations referred to in this report (only a portion of those situations studied) is given in Weather Summary on page 4-15.

A summary of corona records illustrated in Figure 4-9 follows.

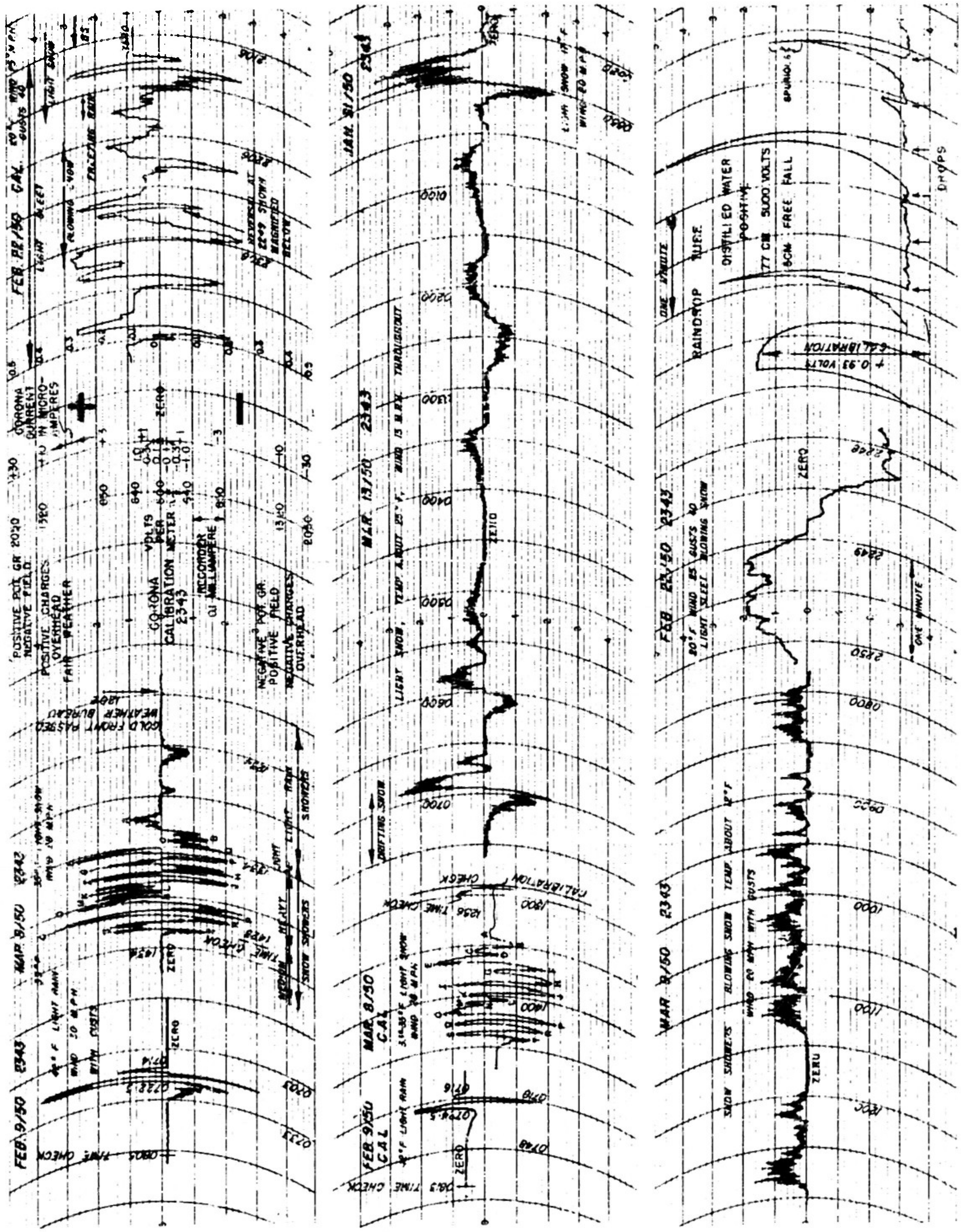

FIGURE 4-9

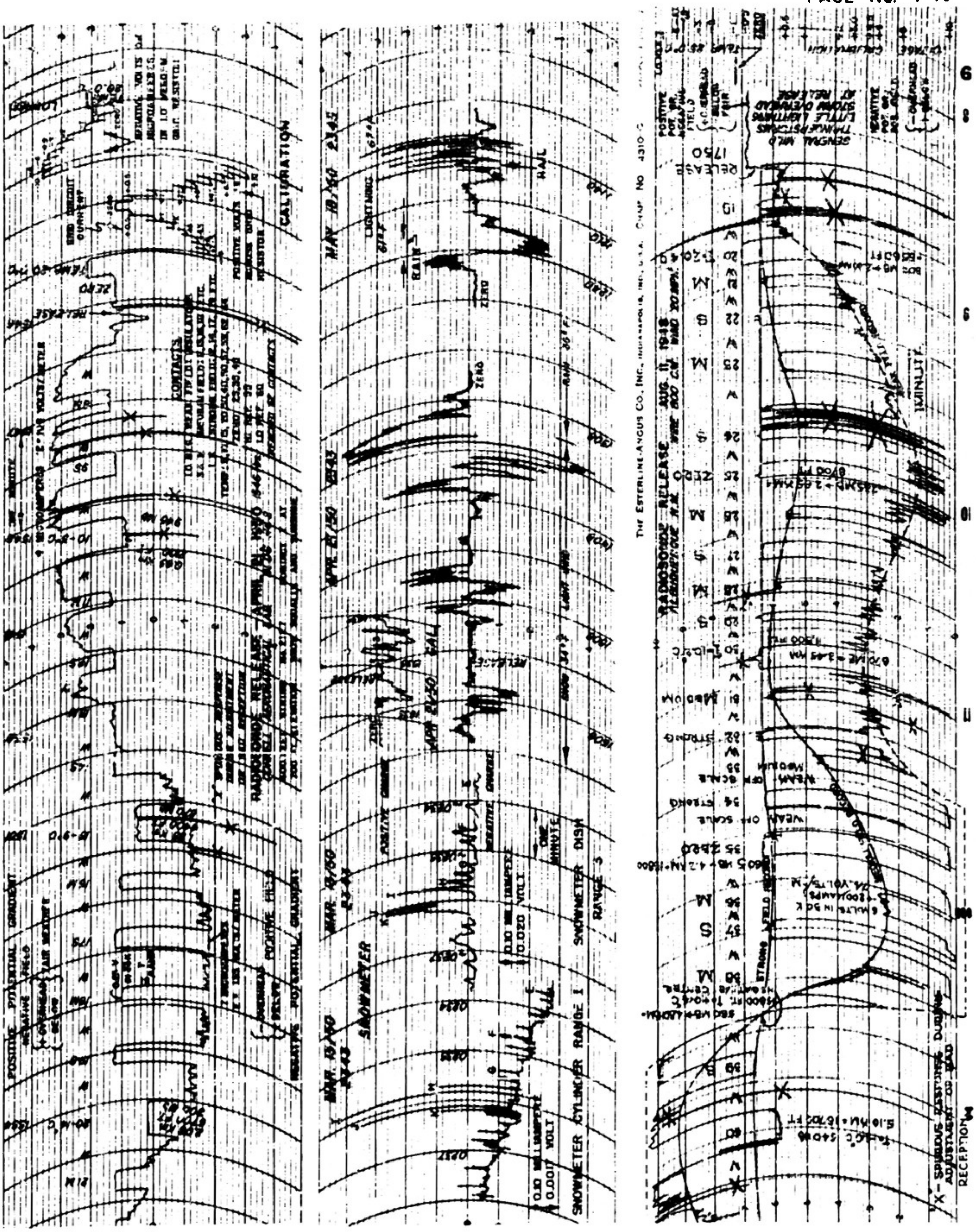

FIGURE 4-10

Corona Records Selected for Illustration

Several corona current records are shown in Figures 4-9. Their somewhat irregular arrangement was intended to fit them on the pages conveniently.

Calibration — The corona current calibration is based on assumptions explained in the section on Corona Point Instrumentation. The calibration shows the recorder current for various values of the earth's electric field ranging from 500 to 2,000 volts per meter, and the corresponding corona currents to the corona point ranging from -30 to zero to +30 microamperes. Full scale on the Esterline-Angus chart is 1 milliampere. The recorder ordinarily operated with the zero current in the center of the scale so that the chart readings are -0.5 to zero to +0.5 milliampere. A record in the upper part of the chart shows the earth's potential gradient to be positive corresponding to a negative field (typical of fair weather) and represented by positive charges overhead. A record in the lower part indicates a negative potential gradient or positive field with negative charges overhead. This calibration applies to the corona point at 2343 Kensington Avenue.

31 January 1950 — Light snow. Temperature 17°F. Wind 20 mph. Short Asymmetrical record. Zero has drifted slightly.

9 February 1950 — Light rain and drizzle. Temperature 42°F. Records are shown both for the 2343 corona point and the C.A.L. corona point. These records are typical of short, rapid field reversals, and fields of considerable strength. The time interval of the displacement of the recorder from the usual reading of zero corona current, is less than 20 minutes,

i.e., electrical effects were short-lived. Such records are quite frequent. The C.A.L. recorder being over-damped (see text) responds more slowly than the 2343 point. Normal rate in both charts: 1.5 inches per hour. There has been a small drift of the zero corona current from the center line of both records. Note the asymmetry of the record in time.

22 February 1950 Sleet, snow, blowing snow, freezing rain. Temperature 20°F. Major snowstorm. C.A.L. record at normal 1.5 inches per hour for 3 hours duration of storm. Zero has drifted considerably. Traces typical of long storm of moderate activity. Field reversals not unusually frequent. A portion of the 2343 record is at the expanded rate of 1.5 inches per minute. Note rapid field reversal within interval of 60 seconds; no visual change in storm conditions during this reversal. C.A.L. recorder being overdamped shows much less structure than 2343 recorder. In 2343 record, note rapid fluctuations typical of snowstorms.

8 March 1950 Light snow. Major electrical activity. Cold front passed U. S. Weather Bureau Airport Station at 1202, about two hours before greatest activity with light snow falling. Frequent and rapid field reversals. No apparent visual change in sky or storm conditions during reversals. As usual, 2343 record shows more structure than C.A.L. record. Similarity of record at the two stations 1.7 miles apart is really striking, especially if one record may be superposed on the other during examination. Time synchronization shown in detail in Corona Time Records. C.A.L. zero has drifted somewhat from the centerline of the record, and in superposing records, one should take notice of the fact that a fixed time is represented by a curved arc as

shown. Hence when the zero is displaced, as here, it is not possible to line up ordinates of both positive and negative polarities simultaneously. Some corresponding deflections are marked with letters A, B, C, etc.

9 March 1950 Trace of precipitation. Blowing snow. Temperature 11°F. Record is typical of light activity except for the unusual feature that all potential gradients are positive. Ordinarily both polarities are observed. This single polarity was once reported by Simpson for blowing snow. Imaginative persons may try to infer some periodicities in the record at intervals of 20 to 30 minutes.

13 March 1950 Light snowstorm. Temperature 23°F. Record is typical of light activity. Slow reversals of polarity. Snowmeter was being operated (see text and Figure 4-9) at about 0200 to 0300. Asymmetrical records at about 0600 and 0700 are quite typical.

21 April 1950 Portion of snowstorm characterized by snow squalls and sunshine. Temperature about 35°F. Radiosonde release made at 1546 from C.A.L. station shown in Figure 4-10. Portion of C.A.L. corona record at the compressed rate of 3/4 inches per hour is shown as inset on the 2343 record which is made of the regular rate of 1.5 inches per hour. Although efforts were made to get the balloon into a good part of the snow squall, it is clear that the release was made at a time when electrical activity was relatively small.

18 May 1950 Thunderstorm and showers. Temperature 67°F. Note that lightning has characteristic trace of spikes quite different from the traces for rain and snow. On an expanded scale the lightning discharge spikes would show field-recovery time-constants of the order of 5 to 20 seconds.

CORNELL AERONAUTICAL LABORATORY, INC.

BUFFALO, N. Y.

PREPARED BY Seville Chapman REPORT NO. VC-603-P-1

Corona Time Records

Date	Hours	Weather	Temp °F	Wind	2343 Hours	C.A.L. Hours	Actual Difference Minutes	Wind Correction Minutes
31Jan50	0515-0615	S-	17	ENE20	X0550	0550.5	0.5	-3.6
9Feb50	0715-0730	R-L-F	42	S30+	C0714	0716	2.0	-1.3
illustrated					X0718	0718.5	0.5	
					X0719.5	0721	1.5	
					X0722.5	0724.5	2.0	
14Feb50	0154-0204	ZR-	30	ENE18	C0150	0151.5	1.5	-3.9
					P0154	0154	0.0	
					X0155	0156	1.0	
14Feb50	1430-1600	R-	36	ESE20	Q1443	1444	1.0	-5
					C1541	1542	1.0	
22Feb50	2115-2400	E-S-BS	20	NE25+	X2123	2122.5	-0.5	-1.5
					X2125.5	2126.5	1.0	
					X2249	2249.5	0.5	
8Mar50	1314-1430	S-	35	SW28	X1324	1327	3.0	+1.4
					P1334	1336	2.0	
illustrated					X1337.5	1340	2.5	
					X1341	1345	4	
					X1344.5	1346	1.5	
					X1349	1351.5	2.5	
					X1351	1353.5	2.5	
					X1355	1358	3	
					P14W	1402	2	
					X1407	1411	4	
					X1411.5	1414	2.5	
					X1414.5	1417	2.5	
					X1418	1421	3.0	
					X1423	1423	0.0	
					8Mar50 Average		2.5	+1.4

A=hail	-=light } (when used with wind data, refers to gusts)
B=blowing	
E=sleet	+=heavy
F=fog	
K=smoke	P=field peak
L=drizzle	X=sharp field reversal
R=rain	
S=snow	C=abrupt commencement of activity
T=thunderstorm	
W=showers	Q=sharp rise
Z=freezing	

CORNELL AERONAUTICAL LABORATORY, INC.

BUFFALO, N. Y.

PREPARED BY Seville Chapman

REPORT NO. VC-603-P-1

Weather Summary

Note: Columns are respectively: date, hour, ceiling in hundreds of feet, sky cover (nearly always completely overcast ⊕, or not observed X), visibility in miles, state of the weather (with standard symbols, R = rain, S = snow, W= showers, see explanation in table on Corona Time Records, page 4-14), sea level barometric pressure in tenths of millibars with the first digit or two omitted, temperature in degrees Fahrenheit, dew-point temperature, wind direction and speed in miles per hour, (+ and - refer to heavy and light gusts), precipitation in inches of water per hour, and remarks.

Date 1950	Hour	Ceil	Sky	Vis.	Weather	BarPr	Temp	DTemp	Wind	Prec	Remarks
31Jan	0545	8	X	1	S-	200	17	12	ENE20	T	Short asymmetric corona record. Time record. Corona Record illustrated.
9Feb	0728	19	⊕ ϕ		R-L-F	041	42	40	S30+	.03	
	0826			5		037					pressure minimum
	0930						45				Corona records illustrated. Time record.
14Feb	0158	33	⊕	6	ZR-	240	30	28	ENE18	.04	
	1503	23	⊕18ϕ	6	R-	139	36	34	ESE20	.05	Pressure falling rapidly. Time record.
22Feb	2106	11	⊕ ϕ	3	E-S-	007	20	16	NE24+		G40 no front.
	2128	10	⊕	3	E-S-	983	20	16	NE23+	.11	G35 radiosonde release
	2139	10	⊕	3	ZR-E-S-				ENE26+		G35 unsuccessful.
	2150	20	⊕	3	E-				ENE25+		G35 Corona records
	2214	16	⊕	3	E-BS				ENE27+		G46 illustrated.
	2230	12	⊕	3	E-BS	959	20	16	ENE26+	.10	G45 Time record.
	2255	13	⊕	1.5	E-BS				ENE25+		G40
	2330	16	⊕	1.5	E-	946	20	16	ENE25+	.16	G40
	0012	17	⊕	3	E-				ENE16-		Occasional ZR- BS 1025-2105 BS 2200-2317 S- cont. to 2145 E- 2105 cont. ZR- 2137-2149
24Feb	1128	8	X	1/2	S	014	28	27	NW13	.10	front passed 1045. wind shift from S18 to NW15 in 7 minutes and Temp33 DTemp33 Radiosonde release 1133.5. successful

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Date 1950	Hour	Ceil	Sky	Vis.	Weather	BarPr	Temp	DTemp	Wind	Prec	Remarks
28Feb	1328	30	⊕	1.5	S-	041	34	30	S20	.03	Pressure falling rapidly about 0930 and 25° 13° SE16 to 34° 30° S18. Radiosonde release 1322.5 successful
8Mar	1400	8	X	1	S-	970	35	34	SW28	T	Front passed 1202. At 1129 46° 42° S22. Corona Records illustrated. Time Record.
	1330	9	⊕ ⌽	1.25	S-	970	35	34	WSW30+	T	G38
	1340	5	X	1	S-				WSW30+		G40
	1400		X	1	S-				SW28+		G40
	1415		⊕	3	S-				SW28+		G38
	1430	50	⊕150⌽	7		976	33	31	SW28+	T	G36
9Mar	0828	45	●	2	SW-BS	108	11	3	W28+	T	G40 SW-0745 to 1325
	1130	18	⊕	2	SW-BS	149	12	6	W20+	T	G38 BS 0800-1405
	1405	25	⊕	7	SW-	173	18	4	WNW36+	T	G52 Corona record illustrated.
13Mar	0026	12	X	2	S-	173	25	18	NE15	.05	Pressure falling rapidly snow 0005-1002 snowmeter operated. Drifting snow until 0829
	0229	8	X	1	S-	152	23	20	ENE14	.05	
	0648	5	X	3/8	S	108	21	17	E22	.05	
	1041	12	●	7	ZR-	081	28	21	ENE18	.02	ZR until 1126 then ZR 1223-1308. Corona record illustrated.
17Mar	1201	170	⊕	10	clear	095	31	12	S5		Pressure falling rapidly
	1527	12	X	1	S-K	017	32	28	S14	.02	Pressure falling rapidly
	1628	8	X	3/4	S-	990	31	29	S18	~.08	Pressure falling rapidly
	1828	6	X	1/2	S	949	32	31	S26	.02	Radiosonde release unsuccessful
	2027	5	X	1	SBS	937	31	30	W20	~.08	Cold front passed 2000E with thunderstorm, one lightning
	2029	6	X	1	S-BS	949	31	30	W20		
24Mar	1528	19	● ⌽	3	K	064	39	34	WSW8	none	Radiosonde release 1502 successful
13Apr	1330	15	⊕	1.5	SW-	163	22	20	WNW16	T	half sunshine.
	1428	12	●	1.5	SW-	163	23	19	SW8	.01	large flakes. Radiosonde release 1342.5 successful

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Date 1950	Hour	Ceil	Sky	Vis.	Weather	BarPr	Temp	DTemp	Wind	Prec	Remarks
21Apr	1005	10	⊕	8	SF-				8		
	1027	6	⊕	2	RW-SW-	139	36	33	WNW11	.03	throughout
	1053	4	⊕	3/8	TSW						Lightning
	1129	15	⊕	7	SW-		35	33	NW13	.03	
	1224	16	⊕	8	RW-	142	36	34	NW10		
	1324	6	⊕	5	SW-				NW10	.03	
	1330	6	⊕	3/4	SW-	142	36	33	NW12		
	1430	5	X	1/2	SW	142	34	33	SW10		
	1529	7	⊕	1	SW-	149	34	33	SW13		
	1530										Radiosonde release
	1628	20	⊕	1.25	SW-	156	34	34	SW10		1546 successful and
	1630										illustrated. Corona
											records illustrated.
18May	1147	23	⊕	4	T RW A	125	67	57	NW16	.06	Hail 0.5 to 1 inch
											diameter, thunderstorm.
											Corona record illustrated.
	1229	40	⊕	7		125	61	56	NNW18		
	1231	20	⊕	6	RW-Q				NNW17		
	1241	16	⊕	6	RW-A				NNW18		
	1243	18	⊕	8	RW-				NNW30		
	1301	100	⊕	10					N26		
	1328	50	⊕	10		122	59	55	N28		
	1415	50	⊕	10					NNE17		

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V. THE RADIOSONDE INVESTIGATION

Introduction

Since the upper parts of thunderclouds contain snow crystals, as mentioned in Chapter III, it was felt that by studying snow electrification on the ground, we might make some progress in understanding electrification in the upper parts of thunderclouds. As discussed in Chapter IV on the corona point investigation, it became clear that considerable atmospheric electrification was generated in snowstorms. The corona point near the ground could measure snow electrification brought about either by conditions local to the ground such as snow blowing along the surface of the ground, or by general atmospheric processes in the entire snowstorm. To supplement the corona point records, therefore, it seemed desirable to investigate the electrification in the upper atmosphere, at least to an altitude of a few miles.

The atmospheric electric field in thunderstorms had been measured previously by means of modified radiosondes by members of our staff, and a number of radiosondes left over from that earlier work were available. Accordingly, plans were made for radiosonde investigations of snow electrification during blizzards.

In brief, the standard type of radiosonde is modified so as to measure the vertical component of the atmospheric electric field, and is carried aloft by a balloon during a blizzard. The signal from the radiosonde is recorded on the ground. By appropriate data reduction one can determine the electric field in the atmosphere along the path followed by the balloon. From the electric field one can infer the charge distribution in the snow clouds. A detailed description of the radiosonde used in this investigation will not be given in this report and the reader is referred to Reference 4 for further information.

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Brief Description of Radiosondes

The radiosondes used were the standard type AN/AMT-7 operating at a frequency of 403 megacycles per second. This instrument is designed to be carried aloft by a free balloon to measure the temperature, humidity, and pressure of the atmosphere through which it passes. On the ground during a high wind, the 6-foot diameter balloon is handled by a shroud.

A radiosonde contains a radio transmitter which is suitably modulated by a temperature sensitive element, a humidity sensitive element, and a barometric pressure switch called a baroswitch. The radiosonde transmitter consists of a pulse-modulated 6N4 power oscillator tube tuned by a half-wave line, and tunable over a frequency range of approximately 390 to 410 mc/sec. Oscillations of the 6N4 occur when a modulating 3A5 blocking oscillator tube is on. When the 3A5 is blocked, the 6N4 is off and no signal is received from the radiosonde. The modulator tube, a 3A5 dual triode, operates as a blocking oscillator which is controlled by the resistance of the temperature and humidity in its grid circuit. Its second section is a buffer which pulse modulates the 6N4 power oscillator through a small pulse transformer. The frequency of the blocking oscillator is influenced not only by the resistance in its grid circuit, but also by any grid bias applied to its grid circuit. In the standard model radiosonde, no special bias is applied, although the development of a bias by an additional tube is the fundamental basis of our modification.

The temperature and humidity elements are switched one at a time in and out of the grid circuit by the baroswitch. The baroswitch also places fixed resistances in the grid circuit, corresponding frequencies of which are called high reference and low reference. The sequence of temperature, humidity, high reference and low reference is predetermined by the sequence of contacts and insulators of the baroswitch. There are 80 contacts on the standard baroswitch, each one corresponding to a certain pressure. By this switching procedure, the baroswitch indicates pressure and also serves to interchange temperature, humidity, and reference elements. Approximate altitudes and pressures are shown in the table on page 5-3.

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APPROXIMATE RADIOSONDE CALIBRATION

Contact	Pressure millibars	Height kilometers	Height feet
4	1,020	0.00	[illegible]
6	990	0.25	[illegible]
8	960	0.50	[illegible]
10	930	0.77	[illegible]
12	900	1.05	[illegible]
14	870	1.35	[illegible]
16	840	1.65	[illegible]
18	812	1.94	[illegible]
20	788	2.17	[illegible]
22	762	2.41	[illegible]
24	736	2.70	[illegible]
26	710	3.00	[illegible]
28	684	3.25	[illegible]
30	659	3.55	[illegible]
32	633	3.86	[illegible]
34	606	4.20	[illegible]
36	580	4.54	[illegible]
38	553	4.90	[illegible]
40	525	5.29	[illegible]
42	500	5.63	[illegible]
44	475	6.00	[illegible]
46	450	6.43	[illegible]
48	425	6.85	[illegible]
50	400	7.26	[illegible]
52	375	7.75	[illegible]
54	350	8.26	[illegible]
56	325	8.86	[illegible]
58	300	9.40	[illegible]
60	275	10.0	[illegible]
62	250	10.6	[illegible]
64	225	11.3	[illegible]
66	200	12.0	[illegible]
68	175	13.0	[illegible]
70	150	14.0	[illegible]
72	125	15.2	[illegible]
74	100	16.5	[illegible]
76	75	18.[illegible]	[illegible]
78	50	[illegible]	

The radiosonde signals were received on APR-4 radar receivers, the output of which was fed to a linear audio-frequency frequency-meter whose output was 1 milliampere for a frequency of 200 cycles per second, and was zero at zero cycles per second.

The frequency meter circuit is discussed in Chapter VI and is shown in Figure 6-39.

The antenna used for the receiver was a 5 turn helical antenna, wound with 0.5 inch diameter aluminum tubing, having a helix diameter of 10 inches and a pitch of 7.5 inches. An appropriate matching stub was inserted at the antenna where it connected to the RG8U cable, which led to the antenna plug of the receiver. No specific measurements were made on the performance of the helical antennas, but it was observed in practice that they were "quite directional", so that the gain was probably of the order of 10 db. In view of the fact that high winds commonly accompany blizzards, and the elevation of the radiosonde was frequently quite small, it was important to have as much gain as possible in the receivers. The comment in Reference 4 on the desirability of frequency modulated rather than pulse modulated radiosondes should be emphasized again, since it is impossible to distinguish between zero frequency and no signal with a pulse modulated radiosonde (i.e. one does not know whether the field is strongly positive--negative charges overhead, positive below--or whether he has lost the signal).

Radiosondes had two labels on them marked "DANGER--DO NOT TOUCH WIRES OR STRINGS--READ INSTRUCTIONS" in large red letters and also two smaller labels requesting the finder to return the radiosonde to the Laboratory. A mailing tag was fastened under the top flap. Some of the radiosondes were returned in pretty bad shape and were used for spare parts.

Radiosonde Modification for Measurement of Electric Field

In order to make the standard radiosonde sensitive to electric field strength, it is necessary to add instrumentation which is sensitive to electric field and which can control the blocking oscillator at frequencies for which

it was designed. In previous radiosonding experiments, the modified circuit and instrumentation could handle a field strength ratio of approximately 200 to one in three ranges, each covering a ratio of approximately six to one in field strength. The modification consists of a single tube, a 1T4 remote cutoff pentode with a 1 megohm series grid resistor to give a remote saturation characteristic as well. The various batteries and resistors required for the modification are so chosen that voltage appearing at the grid of the 3A5 modulator tube causes mid-scale modulation frequency when there is no voltage applied to the grid of the 1T4.

Corona current from a trailing wire described below flows through the 33,000 ohm or 1 megohm grid resistor of the 1T4, thereby resulting in a voltage being applied to its grid. The output of the 1T4 then modulates the radiosonde transmitter to which it is connected at points A and B in Figure 5-11, in accordance with the magnitude and polarity of the current flowing through the corona wire. The 0.001 microfarad capacitor in the grid circuit of the 1T4 and the 1/25 watt neon bulb prevent overload or damage of the 1T4 by a radio frequency power which might be picked up on the corona wire acting as an antenna or by excessively high voltage drops which might occur in the event of very large corona currents, respectively.

A special baroswitch commutator was used in each radiosonde so that more channels could be received than with the regular baroswitch. In Figure 5-16 Special Radiosonde Baroswitches, it is seen that one channel of information may be obtained from contacts 1, 3, 6, 8, etc.; another channel may be obtained from contacts 2, 4, 7, 9, etc.; another channel from the insulators; another channel from contacts 5, 10, 15, 20, 30, 40, 50, 60, 70, 80; and a final channel from contacts 25, 35, 45, 55, 65, and 75. A judicious selection of various contacts and channels was made in the snow electrification experiments. We generally used a weak field range and a medium field range, together with temperature channel, a "zero-field" reference (to check drift of zero in the radiosonde--ordinarily drift was negligible), and a few high or low references. Humidity ordinarily was not measured. Just prior to release

the radiosonde was calibrated for input voltages and currents by a "Calibrated Calibrator" shown in Figure 5-15, from which a whole range of positive and negative voltages and currents could be obtained.

The term "weak field" refers to that rather weak electric field which registers on scale when the corona current goes through the 1.0 megohm 1T4 grid resistor. When the radiosonde is in a weak field, the "medium" and "strong" field ranges read zero. When the balloon gets into a field of sufficient magnitude to keep the "weak field" range just off-scale, the "medium" range registers on scale since the corona current then is shunted through a 33,000 ohm grid resistor. In very strong fields, when the "medium" range is just off-scale, the "strong" field range begins to read something other than zero, since the corona current now is shunted through a 1,000 ohm resistor. Quantitatively the three ranges cover a range of about 40,000 to 1 in corona current or 200 to 1 in field strength.

The information telemetered to the ground by the radiosonde was actually the corona current flowing in a trailing wire. Three feet above the radiosonde is placed a corona point consisting of a Recoton Superchrome phonograph needle having a tip radius of approximately 0.003 inches. It is connected to the chassis of the radiosonde transmitter. A similar corona point at the lower end of the trailing wire is connected to the grid current of the 1T4 buffer amplifier so that the DC corona current (of the order of microamperes) flows through the grid circuit and the 1T4 modulates the audio frequency transmitted by the radiosonde in accordance with the magnitude and polarity of the corona current. As shown in Reference 4, for the particular phonograph needles used, this arrangement for corona current measurement yields the following relationship between the electric field E in volts per meter existing in the atmosphere in the absence of the radiosonde, and the corona current i in microamperes:

$$E_{volts/meter} = \frac{53\, P^{0.5}_{millibars} \left(1 + \sqrt{12\ i_{microamperes} + 13}\right)}{L_{meters}}$$

where L is the distance in meters between the upper point and the lower point and P is atmospheric pressure in millibars. As pointed out by Dr. M. M. Newman, this relationship ignores any current which may escape from the sides of the wire. Since the corona point has two degrees of curvature, and the wire has only one degree of curvature, it seems reasonable to suppose that most of the currents will be to and from the corona point at least up to currents of microamperes, and hence travel through the wire in the grid circuit of the modulator. Dr. Newman indicates that this result may not necessarily occur when the currents are of considerable magnitude. In one case he says that at half a million volts he obtained several milliamperes current, of which only 10 percent came from the point. Because of the square law relationship between potential gradient and current (at current ranges greater than a few microamperes) an increase in current by a factor of ten would increase the field by a factor of about 3.2. In Reference 4, we discussed a case where we had measured a field of more than 200 volts per centimeter in a thundercloud. Gunn gives a case where his airplane was struck by lightning when the undistorted field was 1600 v/cm (3400 on the belly of the airplane). He also refers to average maximum fields of 620 volts/cm. The conclusion would seem to be that while corona measurements may or may not give low values of field strength based on our calibration, the values are certainly not low by an order of magnitude.

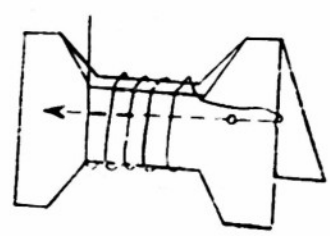
Actually, in the snowstorm work we did not use a trailing wire but rather a conducting string. An effort was made to secure a string which had as few little fibers sticking out from the sides as possible, but it is likely that under conditions of high fields some of these little points would go into corona. Since the radiosonde was not placed in the center of the trailing string but rather a mere three feet from its upper end, if a little fiber were above the center of the trailing string and below the radiosonde, any corona current to it would not be registered by the radiosonde. The electric field readings then would be low.

There is some evidence that the corona-current-voltage relationship may become more nearly linear and less quadratic at high voltages. Dr. Newman

has data, however, up to 1200 kilovolts and 2.85 milliamperes for a point 9 feet from a ground plane which fits the quadratic relationship very well. One seems to be justified in saying then, that radiosonde corona current measurements yield atmospheric potential gradients that are certainly not too high.

The conducting string had a resistance of approximately 0.5 megohm per foot, sufficient so that if the string fell over a power wire, and it was picked up by an individual, he could not receive more than an unpleasant shock; but for a typical situation in the air in which the corona current would be of the order of 100 microamperes or less, the voltage drop through the string would be negligible compared to the potential difference in the atmosphere between the two points.

In some releases, a trailing conducting string as long as 1,000 feet was used. In a strong wind it is a considerable problem to release a balloon with such a trailing string without permitting the point at the bottom to trail on the ground, and hence, perhaps to have its calibration modified. Numerous people made numerous suggestions as to how the string should be unwound from the radiosonde during release, and a number of very elaborate suggestions were made. The most effective method turned out to be one of the simplest. A rather strong cardboard filing folder was cut so that it had a cross section of an ordinary spool. The lower point was placed inside the filing folder protected by the fold, and the trailing string was merely wound around the folder as on a bobbin. The aerodynamic resistance to the unwinding of the bobbin-like folder could be adjusted by making the tabs or ears of the bobbin of appropriate size. While it is true that the bobbin unwound faster at the very start of the release when the balloon was going up relatively slowly, ordinarily the folder would fall away from the point to the ground while the point was still within 100 or 200 feet of the ground. With the exception of the substitution



METHOD OF UNWINDING RADIOSONDE TRAILING STRING
FIGURE 5-8

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of the filing-folder-bobbin for the movie reels used in the thunderstorm work, the release procedure was essentially similar to that described in Reference 4. Because Buffalo has considerable airplane traffic, we obtained clearance from the airport control tower for all releases. Ordinarily this safety precaution caused no delay of consequence.

Instructions for Modification

This section is inserted for the record, and probably is of little concern to anyone other than a technician doing the work.

To modify the normal AN/AMT-7 radiosondes for corona current measurement, the following parts are required:

two	Eveready minimax no. 412 B-battery, 22.5 volts for miniature radios, etc.
one	Volume control IRC D-13-128, 100,000 ohms (dimensions very critical--and must not be more than 1 inch diameter, 1/2 inch deep, and 1/2 inch shaft).
one	1T4 tube.
one	Socket for 1T4 tube (e.g. suitable "glass button miniature" socket having some sort of metal rim so that the rim can be soldered to present chassis).
one	Small tie-point with two insulated points about 1/2 inch apart with one point between which may be soldered to present chassis.
one	0.001 mfd paper capacitor--150 volts or more.
one	No 1 flashlight cell 1.5 volts.
one	1/4 watt neon bulb without base.
one	1/2 watt 10% resistor 1000 ohms.
one	1/2 watt 10% resistor 8200 ohms.
one	1/2 watt 10% resistor 33,000 ohms.
one	1/2 watt 10% resistor 47,000 ohms.
two	1/2 watt 10% resistor 1 megohm.
one	Special baroswitch commutator.
two	Danger labels.
two	Instruction labels.
one	Mailing tag.
one	1/4 inch dowel rod 18 inches long.

Miscellaneous:

hook-up wire, solder, glue, shellac polystyrene dope, tape, nuts, bolts, etc.
upper corona point
lower corona point and folder
necessary string (record length)

The radiosonde circuit modification is shown in the drawing, Figure 5-11. The specific steps required to modify the radiosonde are as follows:

Radiosonde Modification Procedure

Note: Keep a separate record to see that every step has been followed. These released should be valuable and one error can make the release a failure. Final tests should be to verify that everything is OK ratner than to find what is wrong.

1. Starting with a fresh radiosonde, plug in the battery and see if it works using receiver and calibrated calibrator to check temperature and references. Remove battery.

2. Shellac on the two danger labels and two instruction labels.

3. Tie on the mailing label.

4. Punch holes for the dowel.

5. Punch additional hole to right of humidity wire for green wire for grid lead.

6. Take a new commutator, measure resistance between all leads, and between all leads and the brass bolt holding it together. Reject any that shows resistance of less than ten megohms. Be careful of your fingers. Never touch the commutator surface with your fingers. Polish it a bit with crocus cloth.

7. Place new commutator beside the old one and measure their relative length, and record. Contact 80 is on the right end, with the nut. Place new commutator in position so that arm is on proper contact.

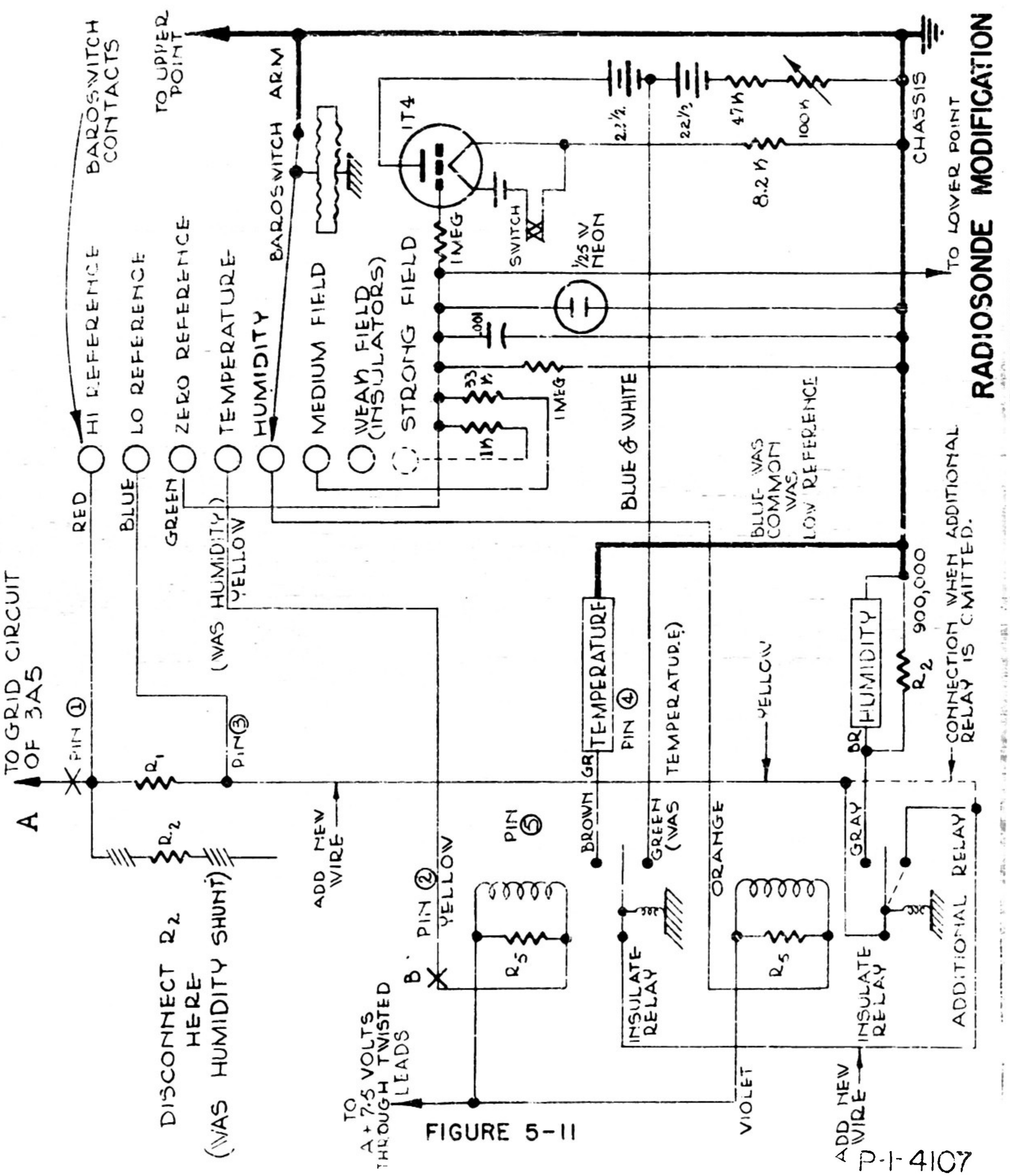
RADIOSONDE MODIFICATION
BAROSWITCH CONTACTS
TO UPPER POINT
BAROSWITCH ARM
HI REFERENCE
LO REFERENCE
ZERO REFERENCE
TEMPERATURE
HUMIDITY
MEDIUM FIELD
WEAK FIELD (INSULATORS)
STRONG FIELD
1T4
22 1/2
47K
100K
8.2 K
CHASSIS
SWITCH
1/25 W NEON
1 MEG
.001
33 K
1 K
TO LOWER POINT
RED
BLUE
GREEN
(WAS HUMIDITY) YELLOW
BLUE & WHITE
BLUE- WAS COMMON WAS LOW REFERENCE
TO GRID CIRCUIT OF 3A5
A
PIN ①
R_1
PIN ③
R_2
ADD NEW WIRE
TEMPERATURE
PIN ④
TEMPERATURE)
YELLOW
HUMIDITY
R_2
900,000
CONNECTION WHEN ADDITIONAL RELAY IS OMITTED.
GR
BR
BROWN
GREEN (WAS
ORANGE
GRAY
PIN ⑤
PIN ② YELLOW
B
R_5
INSULATE RELAY
ADDITIONAL RELAY
DISCONNECT R_2 HERE (WAS HUMIDITY SHUNT)
TO A + 7.5 VOLTS THROUGH TWISTED LEADS
VIOLET
ADD NEW WIRE
P-1-4107

FIGURE 5-11

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8. Snip carefully the leads between contacts 50 and 60 and between 45 and 55, and between 54 and 57.

9. Using spaghetti or insulation tape as needed, connect contacts 5, 10, 15, etc., and 57, 59, 62, 64, etc., to the yellow lead. This now becomes temperature.

10. Connect the measured 33K resistor to contact 78 and the rest of its range and connect green grid lead to the other end of the 33K.

11. Connect contacts 25, 35, 45 to the green lead.

12. Connect contact 2 to a measured 1K resistor and connect the other end to the green lead.

13. Connect 1/25 watt neon bulb between black lead (chassis) and green lead.

14. Connect 55, 65, 75 to blue lead (low reference).

15. Connect 60, 70, 80 to red lead (high reference).

16. Install new commutator and adjust so that it is on the same contact as before.

17. Unscrew relay from case and insulate it from case with a piece of plastic, then glue it down again.

18. Connect 8200 ohms to pin 1, cathode.

19. Connect 1 megohm to pin 6, grid.

20. Connect white wire 7 inches long to pin 7.

21. Connect red wire 4 inches long to pins 2 and 3 (plate).

22. Solder tube socket on under side of chassis with pins 1 and 7 nearest chassis about 1.25 inches from the left (not antenna) end.

23. Solder 8200 ohms to chassis.

24. Solder 0.001 capacitor across the two insulated terminal contacts on terminal strip.

25. Solder measured 1 megohm resistor in parallel with capacitor.

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26. Solder terminal strip to chassis 3/4 inch from left end and ground right terminal.
27. Connect 1 megohm resistor to left end.
28. Connect new green wire to left end and run to baroswitch green wire.
29. At terminal switch disconnect blue wire which comes from temperature element and connect to right end of terminal strip. CAUTION--just because this goes to ground does not mean it can be soldered in any old place--on the back side of the chassis are some easily melted connections.
30. Snip off the 900,000 ohm resistor.
31. Move green wire from temperature element on terminal four from left end and place on terminal 5 where brown wire is, remove brown wire. Cut off about 5 inches of brown wire.
32. Place brown wire on terminal 3 and other end on armature of relay.
33. Saw off shaft of potentiometer close, and cut a screw driver slot.
34. Put 100K potentiometer into slot on right end of chassis with terminals toward end.
35. Bolt.
36. Solder terminal of pot farthest from relay to chassis.
37. Solder 47K resistor to center terminal of pot.
38. Appropriately file terminals of hearing-aid 22.5 volt batteries and tin them.
39. Solder red wire from socket to +45 volts.
40. Solder 47K from pot to -45 volts.
41. Connect the other two ends of batteries together and connect blue wire to them 5 inches long; later goes to terminal 4.
42. Tape up batteries and place in chassis.
43. Solder a different blue wire 5 inches long to pin 1 of 1T4 socket and leave end free, but strip it.

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PREPARED BY Seville Chapman REPORT NO. VC-603-P-1

44. Solder white wire from pin 7 to plus terminal of flashlight battery.

45. Solder white wire 8 inches long to minus of flashlight battery and leave end free, but strip it.

46. Tape the flashlight battery.

47. Twist the insulated parts of the blue and white filament wires together.

48. Strip the blue wire from the B batteries and prepare to solder it to terminal strip 4 before release (and test).

49. Put in the dowel.

50. Wire to upper point connects to black test wire.

51. Wire to lower point connects to green test wire.

52. Before release, the yellow filament wires are twisted together, also the blue and white filament wires, also the blue B+ to terminal four; also the battery is plugged in, and the baroswitch arm is put down. The box must be taped up. The length of wire to the lower point must be known and recorded. The antenna must be put in. String, of course, is tied from the suspension strap to the upper point. A calibration must be made, of course.

53. Step 9 becomes: Connect contacts 5, 10, 20, 25, 35, 40, 50, 55, 61, 62, 63, 64, 66, 67, 68, 69, 71, 72, 73, 74, 76, 77, 78, 79 to yellow for temperature.

54. Step 10 becomes: Connect measured 33K to contacts 12, 33, 67, 89, etc. 56, 57, 58, 59. Connect other end of 33K to green lead.

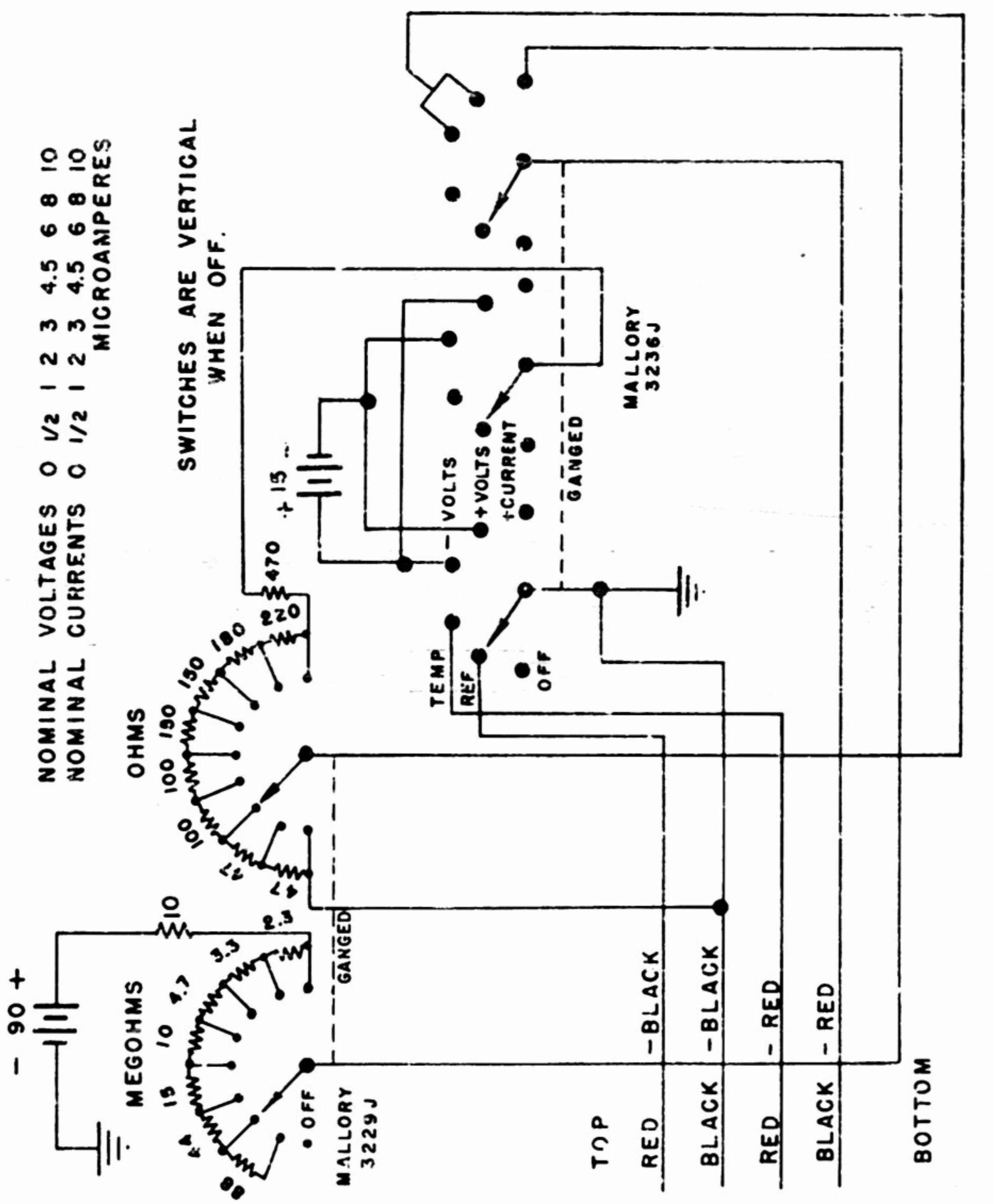
55. Step 11 becomes: Connect controls 15 and 45 to green lead.

56. Step 12 Omit.

57. Step 13 Same as before.

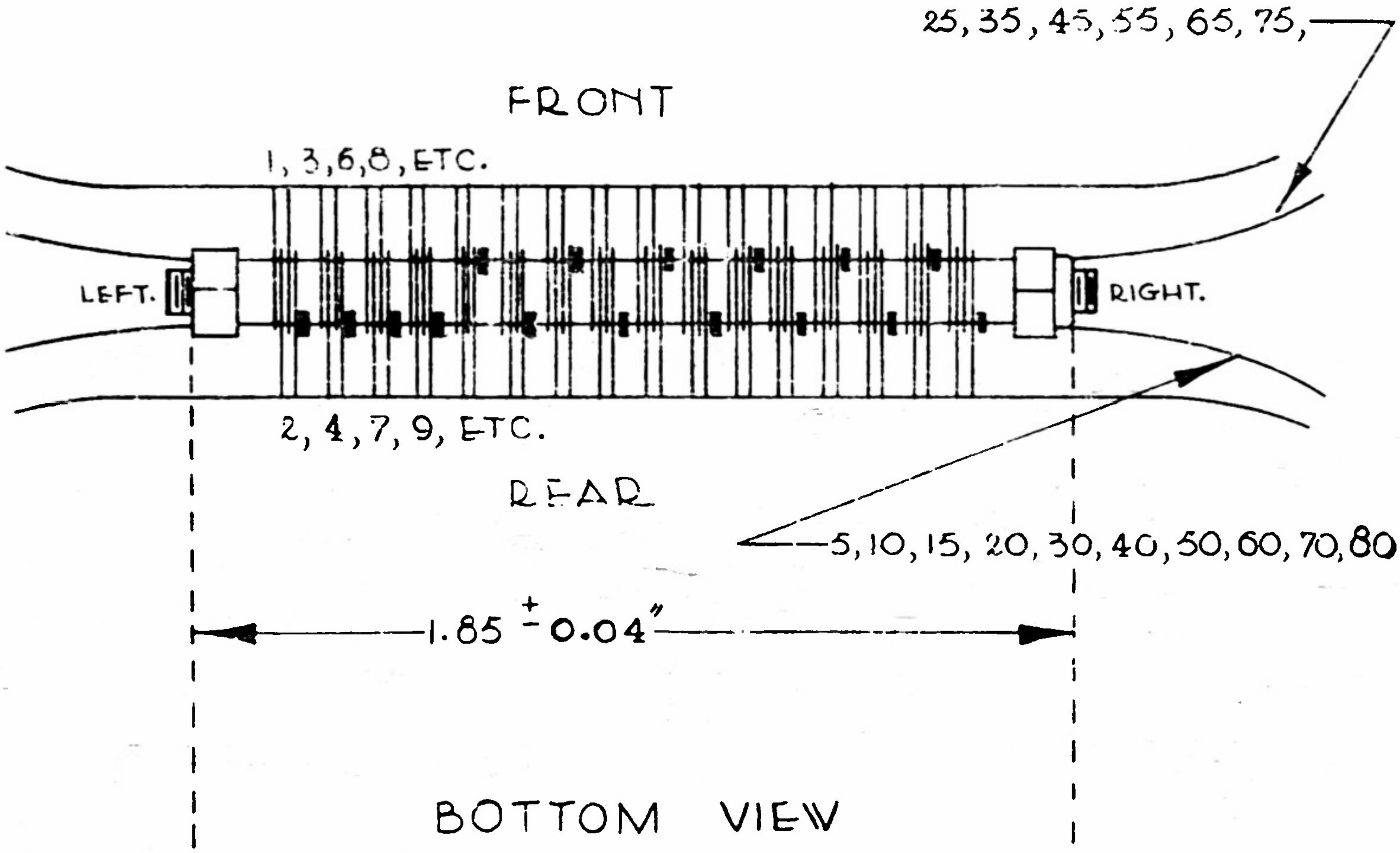
58. Step 14 becomes: Connect 60, 65, 70, 80 to blue low reference.

59. Step 15 becomes: Connect 30 to red, high reference.



CALIBRATED CALIBRATOR FOR RADIOSONDES

FIGURE 5-15



SPECIAL RADIOSONDE BAROSWITCH COMMUTATORS

FIGURE 5-16

Radiosonding Results

Ten radiosonde releases were made during February, March, and April 1950. A portion of one of the records is reproduced in Figure 4-10. In the record, time proceeds from the right-hand end of the record toward the left.

Prior to release, a ground calibration of the radiosonde is made showing the recorder ordinates for various voltages and currents applied to the grid circuit of the buffer amplifier in the radiosonde. These voltages or currents simulate the corona current subsequently measured in flight. In the present example, for instance, 62.5 ordinates represent zero corona current. One of the reference channels, the low reference is shown at 98 ordinates. The temperature circuit is completely independent of the corona current measuring circuit, and with the exception of its appearance on contacts different from those as originally supplied by the manufacturer, its circuitry is completely unmodified. Its precision should be equal to that of releases commonly made by the weather services. The radiosonde was calibrated in the C.A.L. Gate House, and the temperature in the radiosonde temperature duct was 20.0°C. Several minutes later the release was made at 1546 hours.

The day of the release was characterized by snow squalls interspersed with sunshine. The ground temperature was approximately 34°F. An SG-6 radar (6cm) radar was used to observe the approaching snow squalls from a distance of 5 or 10 miles. (Rain storms could have been seen much farther.) An effort was made to get the balloon into the middle of one of the snow squalls and the release was made at 1546. The first eight minutes of the ascent are reproduced. At this time the balloon had reached an altitude of approximately 8,000 ft. Above this altitude no electric field results of any interest were obtained since the corona current was zero, although the radiosonde eventually reached an altitude of 7 miles. While some currents were observed on the descent, the signal faded so much that no useful information was obtained on descent. At no time during the ascent of the radiosonde was it subjected to a particularly strong field. Although the weak field range shows considerable

displacement from zero corona current, the greatest corona current registered was 7 microamperes, which for a 400 foot string, corresponded to a field of 135 volts per meter.

On some of the medium field contacts a displacement of as much as two ordinates can be detected. There was no displacement of the strong field range at any time. The strong field range was used on only a few of the releases; on one occasion a humidity channel was substituted, but more commonly "strong" field contacts were connected to the "medium" range.

The radiosonde record shows that from ground up to 13 contacts the potential gradient was positive (which has the same sense as the fair weather potential gradient) but that it was reversed between contacts 13 and 22. The corona point records for 21 April 1950, also shown in Figure 4-10, indicate that this release was made at a time followed by only slight electrical activity, and it is not surprising that strong fields were not encountered.

A summary of results of the ten releases made on the project is shown (on pages 5-19 and 5-20) in the table: Radiosonde Summary. Of the ten releases four were definitely unsuccessful, and although two other releases were satisfactory they produced no significant results. Four gave useful records. Considering the facts that the releases were made in the most unfavorable circumstances imaginable (snow, high wind, sharp points to be avoided by personnel making the release, and a trailing string several hundred feet long to unwind without touching it to the ground) and that the crew was rounded up hastily when the financial uncertainties of the project were resolved late in the season, the proportion of successful releases seems quite good.

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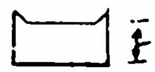
RADIOSONDE SUMMARY

1950 Date and Hour	Rason Number	Ft. of String	Temp $^{\circ}$F	Weather	Remarks
20Feb c1600	2121	200	10°	Calm Clear	Fair weather release for practice. Antenna broke off on release. No record.
22Feb	2124	200	19°		Unsuccessful. Trailing string caught in bushes and pulled off.
24Feb 1133.5	2123	200	28°	Light snow NW wind nearly calm	Fair record. Weak signal. Strong positive potential gradient to 5,000 feet. Negative or reversed potential gradient to 8,200 feet. Zero indication elsewhere. Maximum rason corona current 40 microamperes or about 630 volts/meter potential gradient, which is strongest observed aloft. In spite of field aloft, ground corona points showed very little activity, maximum ground corona current 1.0 microampere.
28Feb 1322.5	2129	400	33°	Light snow moderate south wind	Fair record. Weak signal. Strong positive potential gradient to 3,000 feet. Negative or reversed potential gradient to 5,400 feet. Zero to 6,400 feet. Negative to 10,000 feet. Positive to 12,000 feet. Zero indication elsewhere. Maximum corona current 35 microamperes or about 300 volts/meter potential gradient. In spite of moderately strong field aloft, ground corona points showed little activity; maximum corona current 3 microamperes. 400 feet of string unwound on folder in 47 seconds.  6"
17Mar c1800	2116		30°	Substantial storm, high wind, wet snow	Unsuccessful. Signal faded badly, and essentially undecipherable, since irregular signal makes identification of contacts impossible. Considerable evidence of high fields, but off-scale readings may be associated with loss of signal.
24Mar 1502	2117	1000	41°	Overcast but not actually stormy WSW 10-12	Fair record. Corona points on ground indicating zero current. This release was to attempt to measure "normal" field in overcast weather. Humidity channel used to show cloud thickness. Reached 56 contacts. Potential gradient positive to 4,000 feet, elsewhere zero indication. Results unimportant scientifically since even 1,000 feet of string was insufficient to give record except near ground.

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1950 Date and Hour	Rason Number	Ft. of String	Temp °F	Weather	Remarks
13Apr 1342.5	2134	600	24°	Good storm Large snow-flakes. Visibility one mile. Light NW wind.	Nice record, good storm preceded release. When release was made corona point current momentarily was nearly zero. Subsequent to release, electrical activity shown by corona points was very mild, maximum corona current 1.3 microamperes. Potential gradient positive to 5400 feet, reversed to 8,800 feet, then no further indication until on the descent when it was positive from 8,300 feet to 6,000 feet, whereupon signal faded out. Note that field was normal (positive gradient) on the descent in the same region as it was reversed (negative gradient) on ascent 30 minutes earlier. Reached 52 contacts. Maximum rason corona current of 20 microamperes or about 140 volts/meter potential gradient.
21Apr 1133	2114	didn't unwind, fouled antenna	35°	Major storm Light NW wind. Alternate snow squalls and sunshine.	Unsuccessful. Major storm not precipitating at moment. Light NW wind. Balloon not full enough. String may not have unwound, and may have fouled antenna. OK on part of descent.
21Apr 1411	2133	330	34°	See preceding release.	Unsuccessful. Rason defective or damaged in launching.
21Apr 1546	2127	400	34°	Major storm see preceding releases. Light SW wind Large snow-flakes.	Illustrated in Figure 4-10. Nice record. Good storm with alternate snow squalls and sunshine preceded release. When release was made corona point current was essentially zero and remained less than 1 microampere for several minutes, followed by light electrical activity (see Figure 4-10). Potential gradient positive to 4,000 feet, reversed to 7,500 feet, then no further indication of consequence. Signal on descent too weak for good record. Reached 63 contacts. Maximum rason corona current 7 microamperes or about 135 volts/meter.

The four releases showed positive potential gradients near the ground (positive charges overhead), and all showed negative gradients above. In three cases when the radiosonde reached the altitude where the field was too weak for further indication, the gradient was negative. In one case it was positive. Although there is no significant pattern to these (few) results, one thing is quite clear--that the electrification effects in snowstorms are not local to the ground. In one case the potential gradient was reversed at 10,000 feet altitude.

A possible reason for our obtaining magnitudes of only a few hundred volts per meter for calculated field strength aloft, is associated with the calibration of the long string, as referred to previously in this chapter. The most likely explanation, however, is that the fields really were relatively weak in the region traversed by the radiosonde, but that on occasions they are much stronger, even though we did not have the good fortune to encounter them. For instance, when the corona current to a point 32 feet above the ground is 20 microamperes, it seems likely that the corona current in a 400 foot string above that region might amount to considerably more. While we had currents at the ground of 20 microamperes in the storms in which releases were made, these currents unfortunately did not occur while the releases were in the air, and generally the ground corona currents registered no more than one microampere.

While aircraft have experienced very strong electric fields on their surfaces when flying through precipitation, these effects are associated with the precipitation-static-type of "frictional" charging of the aircraft, and are not an indication of the electric field strength of the atmosphere. To measure electric fields in the atmosphere from aircraft, it is essential to maintain the electrostatic charge of the aircraft at zero by some automatic zero-charging device. Such a system is nearing completion at this Laboratory.

A thunderstorm radiosonde record of August 11, 1948 is reproduced in Figure 4-10 also. This record first appeared in Reference 4, and is included here for interest.

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Recommendations

It seems quite likely that if arrangements could be made before the start of a season to do radiosonding in snowstorms during the middle of the season when the really good storms occur rather than at the end when any "possible-looking" storm must be worked (which costs just as much in man-hours), then balloons could be gotten into the most active parts of storms.

It is natural to ask why the crew cannot be all ready when the forecast is for a storm. (The Buffalo Weather Bureau forecast accuracy is above the national average in spite of the relative difficulty of forecasting for Buffalo.) Unfortunately the forecasts for storms or snow flurries occur for most of the days in the winter, and it is only on rare occasions that the storm is a real substantial one that lasts long enough to be worked effectively (minimum two hours consecutive storm). It would be more reasonable to get the equipment in readiness, and wait until the daily forecast for a storm or flurry materializes into a real storm right at the Laboratory. If operations began at the start of a season (late November), nothing serious would be lost if a given storm didn't work out. When one is trying to work in March he is under too much pressure of the type "this may be our last chance".

All radiosonde releases reported by us (except one) have been made with the radiosonde near the top of the trailing string. Historically our choice of this position arose because of a desire not to be at the bottom of a long vertical conductor while making a release in a thunderstorm. Later thunderstorm work showed that a wire 25 feet long was long enough, though we continued to mount the radiosonde near the top for convenience. In snowstorms with light wind (but only in those cases) it should be possible to mount the radiosonde in the middle of the string.

With a captive balloon in fair weather it should be possible to measure corona currents in a long string, together with a measurement of the earth's potential gradient from aircraft equipped with fieldmeters. Cornell Aeronautical Laboratory presently has projects which involve measurement of electric field aloft. Perhaps useful calibrations can be made.

The electronic gear necessary to make radiosonding records is developed and is available at the Laboratory (see next chapter for indications of the amount of electronic gear involved). A usable stock of radiosondes in various stages of modification still is available. It is recommended that further work be done to determine heights, polarities, and magnitudes; but that the work be done on a somewhat leisurely basis, that is, with the project set up to start in September or before, so everything can really be in readiness by November--even allowing for procurement delays for such things as special batteries--and that only the ideal storms be worked. In this way significant scientific results should be achieved with a minimum of financial expenditure.

VI. ELECTRONIC INSTRUMENTATION

In this chapter, various electronic instrumentation is described. While some features of the equipments represent definite advances in the electronic instrumentation art, there is nothing of geophysical interest in this chapter beyond the application of these devices to atmospheric electricity problems.

DC Amplifiers

Introduction

In order to operate the snowmeter, four DC amplifiers were required. As is well-known by all persons familiar with electronic circuitry, the art of constructing drift-free DC amplifiers with high input impedance such as 10^{12} ohms is not well developed. In fact, the last of the amplifiers developed on thundercloud electrification studies at Stanford University (ref. 4) was probably as good as any as had been developed up to that time. Not all of the Stanford amplifiers, however, had the high degree of performance of the last model. Furthermore, in the delayed transfer of equipment to the Cornell Aeronautical Laboratory, some essential parts of the equipment were omitted. The adjustments of each of the four Stanford amplifiers were quite different, and in the cases of the earlier models, excessively complex. In view of the fact that equipment for field measurements on snow must be capable of being put into operation on a few minutes notice (since storms often have short lives), it was decided to construct identical amplifiers, incorporating the best features of all the Stanford amplifiers plus a few additional features. The time saved by making all amplifiers identical would more than compensate for the extra effort of building one or two which might have been thought to be not entirely necessary. As it worked out these new amplifiers were nearly finished before any of the Stanford amplifiers were received.

Since the electrometer tube characteristics are crucial in the design of a low drift, high impedance, low grid current DC amplifier, it was decided

to obtain data on operating characteristics essentially more complete than ordinarily is obtainable from the manufacturer's few published curves, and to conduct an investigation with the view in mind of reducing drift. The outcome of this investigation was that we were able to construct and operate amplifiers of a sort suitable for this kind of an investigation with 10^{12} ohms input resistance and having performance characteristics exceeding those of some commercially available amplifiers having input resistances of only 10^6 ohms. The discussion follows in two sections, the first on the test of the Victoreen VX41A electrometer tube (now 5800) and the second on the description of the DC amplifiers.

Victoreen VX41A Electrometer Tube and Circuits

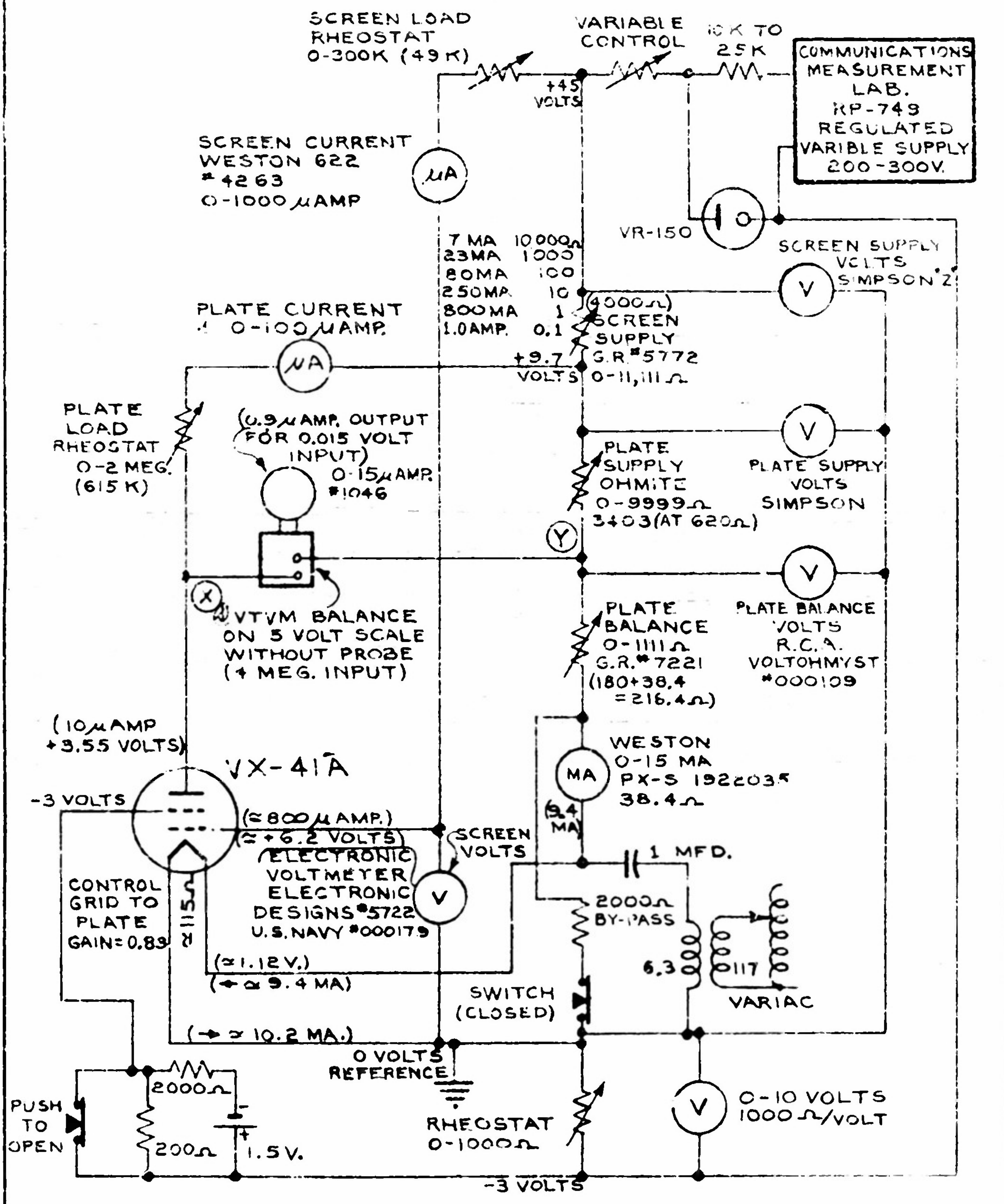
If one is content to operate at input impedances of the order of 10^6 ohms, it is possible to build a non-drift DC amplifier which is so free from drift that a zero adjustment is not required (refs. 13 and 41). Such amplifiers cost several thousand dollars apiece. Their technique of using the chopper and an auxiliary amplifier is not applicable however to the case of very high impedances such as is required for the investigation of this report. The techniques of the dynamic condenser electrometer or the vibrating reed electrometer (refs. 28 and 29) are capable of being used at very high input impedances, but the complexities associated with the necessary motors or vibrators appear to be too great for this application. Accordingly, it seemed desirable to investigate the classical type of DC amplifier circuits with a number of compensating features built into it. Investigations were carried out to ascertain whether it is possible to find a circuit which, in the absence of input signal to the electrometer tube, will yield a constant output voltage from the electrometer tube independent of the voltage supply to the electrometer circuit, and which also is independent of spontaneous fluctuations of cathode emission. In this last connection, it is important to note that in any balanced circuit involving two independent cathodes or even two independent portions of the same cathode (e.g. in type 6J6, spontaneous fluctuations in emission occurring at one point of the cathode will not

be balanced out by spontaneous fluctuations occurring in another portion of the same cathode so that such "balanced circuits" are illusory.

In the space charge tetrode connection of an electrometer tube, the control grid (i.e. grid number 2) does not influence the electron stream until after the electrons have passed through the first, or space charge (screen) grid. Consequently, spontaneous fluctuations in emissions can be corrected at the screen grid before the electron stream gets into the region influenced by the control grid, or at least this is hypothetically the case.

To see if these two objectives (of independence of supply voltage and independence of fluctuations of filament emission) could be reduced to practice, a circuit was set up as shown in Figure 6-4. It is to be noticed that all voltages applied to the circuit, come from the regulated power supply in series with a high resistor and variable control rheostat. Nearly all of the bleeder current goes through the filament of the VX41A electrometer tube. The total bleeder current is slightly more than the nominal 10 milliampere filament current required for that tube. The drawing shows the several circuit elements and also the measuring instruments. The basic thought was that if sufficient resistance were included in the screen grid voltage supply lead, changes in filament emission produced either spontaneously in the filament or by changes in supply voltage so modify the space charge grid current that the screen potential is altered sufficiently to compensate for these changes, and the result in the voltage difference between the VX41A plate, called point "X", in Figure 6-4, and an appropriate tap on the bleeder, called point "Y", being independent of such charges in emission.

The results of several dozen tests appear to warrant the following conclusion. There are many operating conditions under which the potential difference between points "X" and "Y" is independent of supply voltage <u>or</u> is independent of spontaneous changes in emission simulated by supplying alternating current to the filament in addition to the regular direct current.



VX-41A TEST CIRCUIT

FIGURE 6-4

(Of course, one cannot cool the filament to decrease emission, but one can heat it with alternating current to increase emission without significantly modifying DC potentials on the tube.) Unfortunately independence of voltage supply and emission changes do not call for exactly the same operating conditions.

The performance characteristics of what appears to be the most useful arrangement are shown in Figure 6-6. As the filament current is modified by changing the resistance of the variable control rheostat near the top of the bleeder, potential difference between the two points "X" and "Y" is shown on the bottom curve, marked curve "A". The significant result is that this curve has a rather broad, rather level maximum. Without making any modifications in the circuit other than the resistance of the adjustable variable control to vary the filament current, several other curves representing significant parameters of the circuit are shown. It is seen, for instance, that the plate voltage shown in curve "B" rises with increasing filament current even though curve "A" shows that in the range from 9.3 to 9.5 milliamperes the potential difference between points "X" and "Y" remains constant. Curve "C" shows a fairly uniform increase in screen current with increasing filament current. Curve "D" shows the rather unusual shape curve for the screen voltage. It has a very, very broad minimum in the range from approximately 9.4 to 9.9 milliamperes. Curve "E" shows the increase in plate supply voltage with increasing current to the filament through the bleeder. Curve "F" shows the corresponding curve for the same supply voltage.

In another portion of the drawing, a series of curves shows the influence of additional AC heating to the filament of the VX41A electrometer tube supplied with different values of DC current. The abscissae of the two curves are plotted to a scale such that equal distances along the axes of the abscissae correspond to approximately equal increments in filament heating power. It is seen that when the DC current is 9.2 milliamperes, additional heating in the form of alternating current results at first in an increase in change of output or change of potential between points "X" and "Y". Proceeding

RECOMMENDED CONDITIONS:

VX-41A:

e_{pp} = 9.7 V

e_p = 3.5 V.

R_{Lp} = 615 K & 4 MEG. IN PARALLEL

i_p = 10 μA.

e_{ss} = 45 V.

e_s = 6.2 V.

R_{Ls} = 49 K

i_s = 800 μA.

e_{fil} = 1.12 V.

$i_{fil\ in}$ = 9.4 MA.

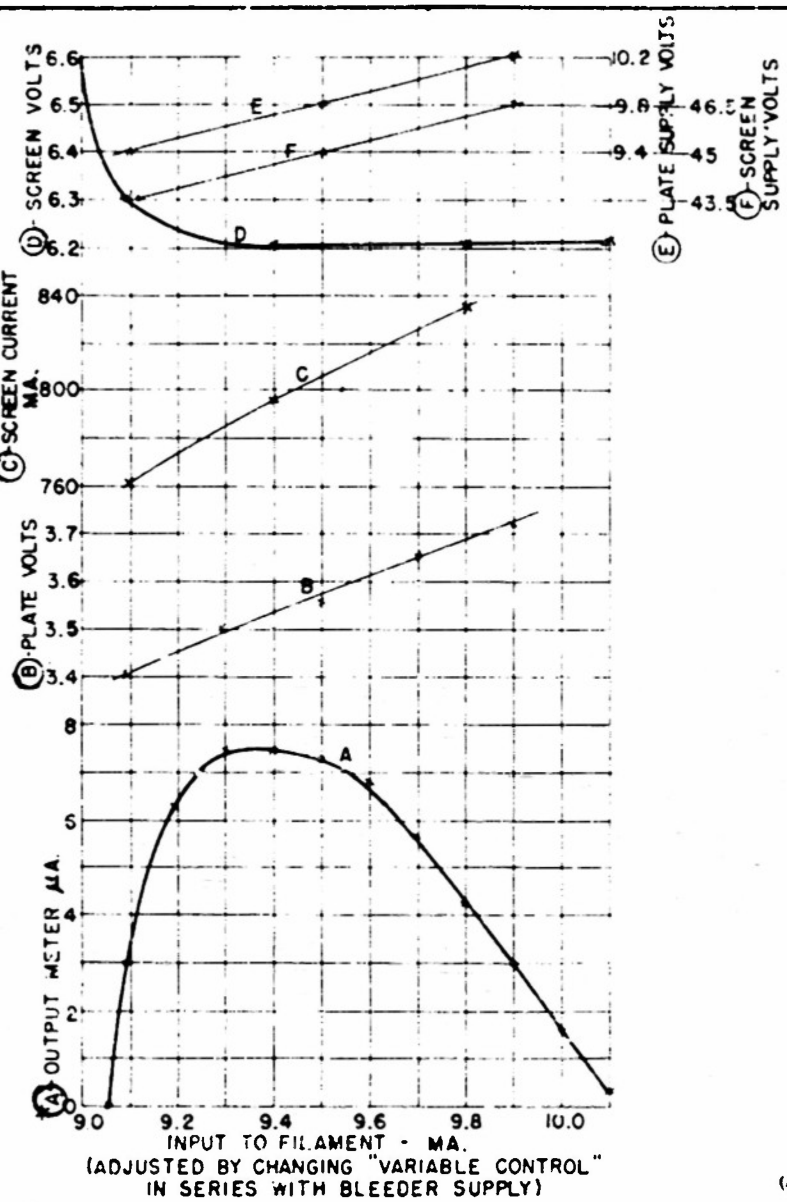
$i_{fil\ out}$ = 10.2 MA

R_{fil} = 115 Ω

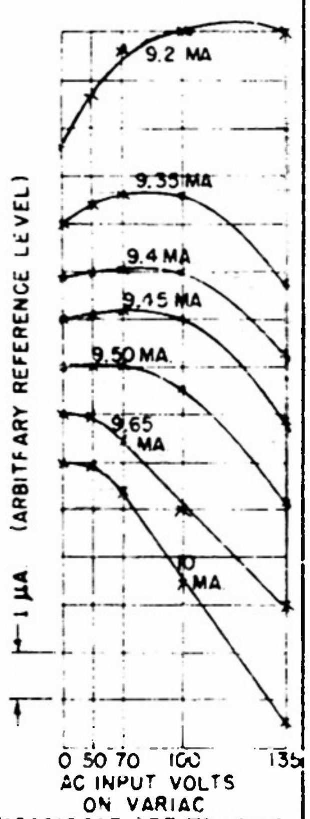
FIL. BY-PASS = 2000 Ω

e_{g2} = -3 V.

GAIN, CONTROL GRID TO PLATE = 0.83



OUTPUT METER MA. AS A FUNCTION OF AC INPUT VOLTS ON VARIAC FOR VARIOUS FILAMENT CURRENTS



(ABSCISSAE ARE TO SAME SCALE AS FOR CURVE A IN RESPECT FILAMENT POWER)

*(A) MEASURES POTENTIAL OF POINT X WITH RESPECT TO Y OF DRAWING P-1-3080 (1 μA. CORRESPONDS TO 16.6 MILLIVOLTS AT CONTROL GRID)

NOTES:

1. CHANGE IN $R_{SCREEN\ LOAD}$ CHANGING i_s BY 15 μA. CHANGES OUTPUT CURRENT BY 4.5 μA.
2. $R_{SCREEN\ LOAD}$ = 3600 Ω, e_{ss} = 42 VOLTS GIVES EQUIVALENT PERFORMANCE WITH A 45 VOLT BATTERY.
3. AV. POWER = $\bar{P}_{AV} = \frac{1}{T}\int_0^T \frac{V^2}{R}\,dt$

$$= \frac{1}{T}\int_0^T \frac{\left(V_{DC} + V_{rms}\sqrt{2}\,\sin\frac{2\pi}{T}t\right)^2}{R}\,dt = \frac{1}{R}\left(V_{DC}^2 + V_{rms}^2\right)$$

HENCE FILAMENT POWER IS INCREASED BY 1.25%, 2.5%, 5% OR 9% BY VARIAC DIAL SETTING OF 50, 70, 100 OR 135 VOLTS RESPECTIVELY, WITH 1 MFD. AND 115-6.3 VOLT TRANSFORMER IN SERIES WITH FILAMENT OPERATING AT 1.12 VOLTS DC.

VX-41A PERFORMANCE IN CIRCUIT P-1-3080

FIGURE 6-6 P-1-3081

through the group of curves for different settings of DC current as the AC current is changed, one finds that at 10 milliamperes DC current, additional AC current results in a decreasing change of potential between "X" and "Y". It happens that the curve for 9.5 milliamperes which shows no change of output with additional AC current corresponds very closely to the peak of curve "A" and the conclusion is that changes in the output potential of the electrometer tube which are independent of DC supply voltage in the range of approximately 9.3 to 9.5 milliamperes DC filament current are also nearly independent of spontaneous changes in filament emission, the changes being nil at 9.5 milliamperes.

Accordingly, the operating condition was chosen as 9.4 milliamperes DC filament current which shows a slightly rising characteristic with increasing emission produced by alternating current, and a slightly falling characteristic with increasing emission produced by increases of DC supply voltage. It was hoped that we could make these two points coincide exactly but our experiments indicate that it was not 100% feasible without the use of separate bias batteries. On the basis of the results discussed above, the DC amplifiers used on this project were designed. Before describing them, it is worthwhile however to record certain points associated with this investigation of DC amplifiers.

A. So far as we know, the simulation of spontaneous changes in emission by the addition of AC heating to the filament has never been carried out previously. It has certain advantages, namely, of changing the filament emission without altering any of the DC biases. If the DC current through the filament is changed, the average bias potential of the filament is altered. On the other hand, the mere addition of AC to the circuits does not necessarily preclude the appearance of AC potentials at other points in the circuit. A careful analysis of the present situation shows, however, that these AC potentials which are in phase with changes of AC potential on the filament are in such phases in the plate and grid circuits as mutually to compensate for themselves in some degree. Furthermore, even at the greatest

AC voltage supplied, 0.33 volts rms, the changes in potential are such as to average to a value that the other DC measurements show to be insignificantly different from the static values without AC. Consequently, it appears that the simulation of emission changes by AC is reliable.

B. The manufacturers' recommended operating conditions differ from those recommended in this report notably with respect to magnitude of screen current. Though not actually shown in any drawing in this report, the curves of the manufacturers' recommended conditions resemble very closely the appearance of the curves shown in this report for a filament current of 10.0 milliamperes showing a marked sensitivity with both DC and AC current supplied to the filament. The question arises as to what accounts for the flat shaped maximum in curve "A" shown in Figure 6-6. It appears that as one goes below a filament input current of 9.2 milliamperes, the filament emission is inadequate to supply the screen current at a reasonably constant potential of 6.2 screen volts. Consequently--and it is very marked when one does the experiment--screen voltage rises abruptly. An increase of screen voltage results in an increase in plate current which results in a decreased plate potential, thereby accounting for the downward slope on the left side of curve "A".

The downward slope to the right of curve "A" is accounted for as follows. The dynamic plate resistance of the VX41A electrometer tube is approximately 100,000 ohms (which is approximately the plate resistance under a large variety of conditions) whereas the static plate resistance under this operating condition is approximately 355,000 ohms. Consequently, if the voltage applied to the whole circuit is increased (increasing the filament current) the potential of point "Y" rises faster than the potential of point "X" so that the potential of point "X" with respect to point "Y" decreases with increasing filament current. While this downward slope could be compensated for circuitwise by insertion of a bias battery between points "X" and "Y", having point "Y" farther down on the bleeder, this arrangement probably would throw out of balance the present balance of the circuit for

spontaneous changes in filament emission simulated by the addition of AC heating current. Furthermore, it would introduce the complication of adding a battery. In any case, it appears feasible to hold the input voltage of the present circuit constant, far within the several percent over which negligible change of output voltage is obtained with the present circuit.

C. The expression in note 3 in Figure 6-6 shown on the drawing for the average power when DC and AC are combined should be noted as well as the accompanying comments explaining why the various Variac dial settings were used.

D. Considerable attention was given to the question of the optimum value of the screen load resistor. In the Figure 6-4 it is shown as 49,000 ohms, but it is not at all critical. Experiments show that as small a value of the screen load resistor as 5,000 ohms worked rather satisfactorily. In fact, the difference between the performance of the 5,000 ohm resistor and curve "A" shown in Figure 6-6 is not very great when there is no filament bypass resistor. If, however, a bypass resistor is used, the reason for which is explained under point E, the curve becomes markedly worse, showing about 150% of the curvature of curve "A". Consequently, it was felt that a 50,000 ohm screen resistor was superior to a 5,000 ohm screen resistor. A 150,000 ohm screen resistor was tried also. This has the significant advantage of enabling one to take the screen supply directly from the VR 150 tube controlling the entire circuit, but the improvement over that for a 50,000 ohm screen resistor was negligible.

The significance of using approximately 50,000 ohms for screen load resistor is that the screen supply voltage is approximately 45 volts which means that a 45 volt B Battery can be used in place of the DC supply from the VR150 tube supplied from a commercial power supply. With a 45 volt battery, the performance using a screen supply of 42 volts above filament minus or 45 volts above B-, together with a screen current is still 800 microamperes, gives performance almost exactly the same as that shown in curve "A" of Figure 6-6. In other words, the reduction of impedance between the screen

supply point and B- has no significant influence upon the performance of the circuit. This point might be of importance in case one wishes to build a portable unit to feed into a commercial DC amplifier. Under these circumstances, a standard 45 volt battery capable of supplying 11 milliamperes continuously could be used and the commercial amplifier could be attached between points "X" and "Y". Presumably, approximately equivalent performance could be obtained from a 22.5 volt battery. As remarked above, however, the performance with only 5,000 ohms screen load was definitely inferior, and would correspond to a total battery voltage of approximately $6.2 + 0.8 \times 5 = 10.2$ volts.

E. The reason for the use of the 2,000 ohm resistor in parallel with the filament is as follows. There is no advantage merely to finding an operating condition which has certain desirable characteristics if, in a practical amplifier, it is a matter of chance as to whether or not this operating condition can be obtained. A convenient means must be provided for adjusting the amplifier rapidly and accurately to the optimum operating situation. After making certain tests and doing some circuit analysis, it appeared that the best and most convenient operating adjustments involved the insertion of a variable bypass rheostat in parallel with the filament carrying approximately 0.5 milliampere or 5% of the total current, the remaining current going through the filament, together with an adjustable control near the top of the bleeder for varying the input voltage slightly. In this manner, it is possible to adjust the filament current over a range of approximately 10% depending upon the bypass adjustment while the supply voltage is varied over a few percent. By noting the response of the output of the amplifier, it is simple to set the filament current at an optimum condition. This procedure was adopted on the amplifier discussed below and shown in Figure 6-13.

F. Throughout the tests, it appeared evident that the plate potential had very little effect on the operating characteristics of the circuit except insofar as it actually varied the plate current itself. A significant parameter appeared to be the filament temperature relative to the magnitude of the

screen current. Under a condition involving a relatively large screen load resistor the screen voltage automatically assumed a suitable operating value. Thus, although the recommended operating condition is -3 volts on the grid, changing this to -6 volts with a corresponding increase in plate voltage to maintain the plate current constant at 10 microamperes has relatively negligible influence on the characteristics of the circuit. Even if the plate current is allowed to drop markedly below 10 microamperes, virtually no effect is noticeable. Conversely, a change to 20 or 40 microamperes plate current (by altering the magnitude of the plate load resistors and changing the plate voltage slightly) has relatively little influence on the performance of the circuit. At 800 microamperes screen current, the curves for both AC and DC at 40 microamperes plate current are indistinguishable within accuracy of measurement from those at 10 and 20 microamperes.

H. Since the magnitude of grid current, which is of the order of 10^{-15} amperes is determined in part by the magnitude of the plate current and in part by the magnitude of the screen current, (and also by grid bias, leakage, etc.) there appeared to be no advantage to allowing the plate current to go significantly above 10 microamperes. At ten microamperes, there is a very satisfactory operating region of linear grid control between -1 and -5 volts.

I. In respect to operating conditions, it is noted in general that the screen current is essentially unaffected by a change of grid voltage. It is true of course that plate current is influenced and hence the plate potential is markedly influenced by grid voltage. The addition of AC heating to the filament clearly does not modify the screen current very much, although it has a very slight influence of a few hundredths of a volt in reducing the screen potential with increasing AC heating. The precision of the measuring instrumentation was insufficient to draw any significant conclusions from this fact. It is to be remembered that the maximum AC heating corresponded to an increase of only 9% power added to the filament.

J. Since the VX41A, like all tubes, is sensitive to photoelectric action when grid resistors of 10^9 ohms or more are used, it must be used in a light-tight box.

K. Tests were made at 340 microamperes screen current, 8.6 milliamperes filament current, 5.0 volts plate voltage, 10.2 volts plate supply, 41 volts screen supply, 10 microamperes plate current, and -3 volts on the grid. The curves differ only very slightly from those at the condition recommended in Figure 6-6. Similar remarks apply to experiments for 460 microamperes.

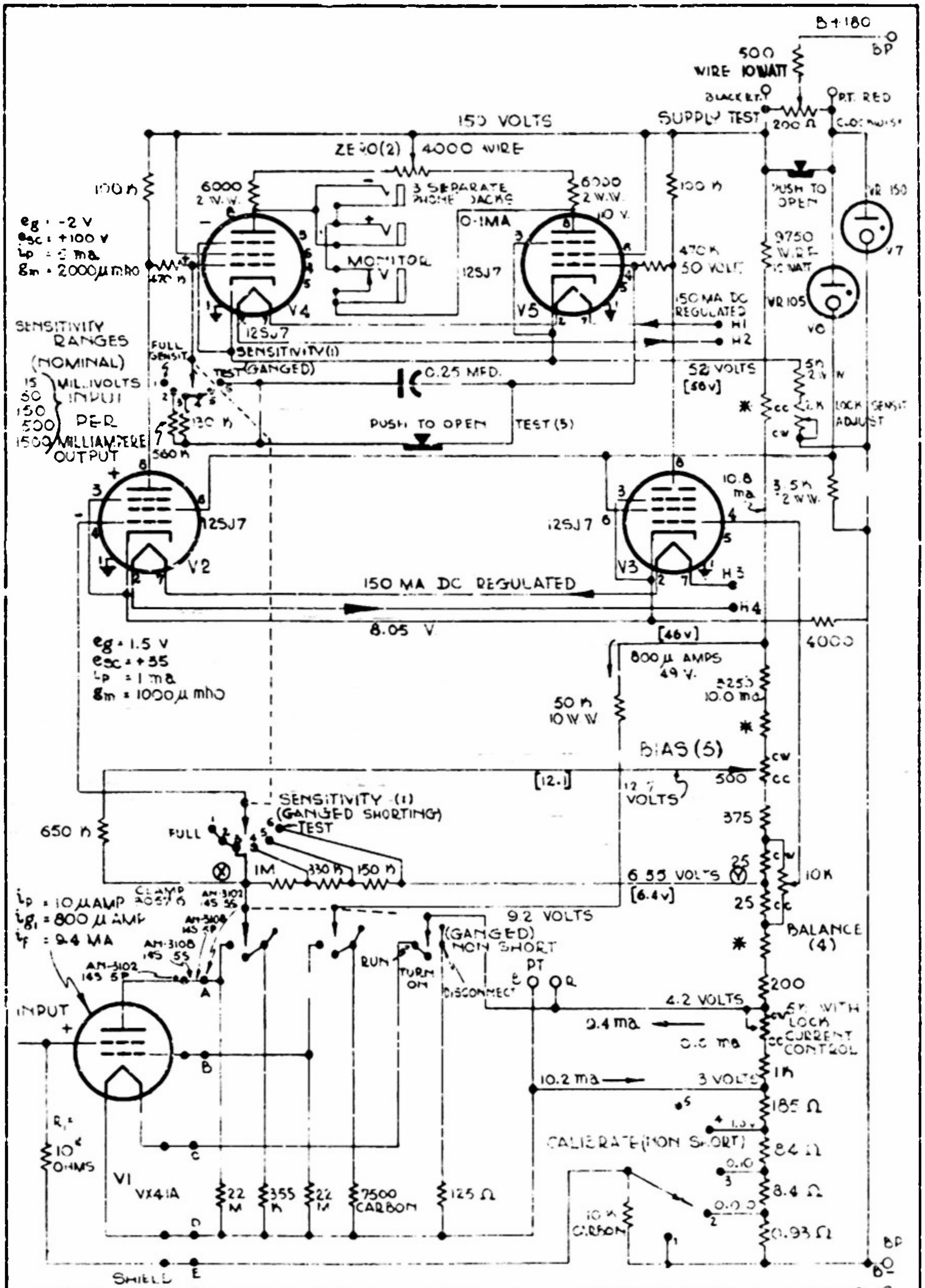
Performance of DC Amplifiers

A DC amplifier capable of operating with grid resistances of 10^{13} ohms or less and having an input range of approximately $\pm$1.5 volts and capable of operating full scale a 0 to 1 milliampere Esterline-Angus recorder critically damped is shown in Figure 6-13. It has nominal full scale sensitivity ranges of 15, 50, 150, 500, and 1500 millivolts input per milliampere output.

The amplifiers operate from the AC power lines without any batteries. Plate supply power, and filament power of 150 milliamperes are provided by separate single stage degenerative regulated supplies. The input circuit is in a probe at the end of a long cable, and may have any resistance up to 10^{13} ohms. The probe consists of the input resistor, and a Victoreen VX41A tube in a special circuit we developed, that compensates for changes in filament supply as well as for changes in filament emission due to age with a constant supply. We obtain drift stability of one millivolt per day when the input resistance is 10^{13} ohms. Noise level is a few times the theoretical limit, and is probably determined mainly by effects of humidity on the input resistor. For our applications we must use the probe in room air, and consequently we have not tried to reduce noise by control of humidity. Short-time fluctuations of the Esterline-Angus

CORNELL AERONAUTICAL LABORATORY, INC.
BUFFALO, N.Y.

PREPARED BY S. CHAPMAN REPORT NO. VC-603-P-1



SENSITIVITY (1)
ZERO (2)
TEST (3)
BALANCE (4)
BIAS (5)
CALIBRATE
RUN, CURRENT CONTROL, SUPPLY TEST, SENSITIVITY ADJUST.

III PHONE JACKS
IIII - - - TIPS
IIII - - - BINDING POSTS
INPUT AN-3102-14S-5S
POWER (B+180, B-, H1, H2, H3, H4)

(* FOR ADJUSTMENT ONLY)

CHASSIS BP

ALL RESISTORS LESS THAN 100 K ARE WIRE WOUND

VX-41A, D.C AMPLIFIER

FIGURE 6-13

P-2-867

recorder correspond to about 0.0001 volt at the input when an input resistor of 10^{11} ohms is used.

The amplifiers are built of standard parts; probably the use of manganin resistors would improve the stability, but the amplifiers are entirely satisfactory for our use now. Grid current is about 5×10^{-15} ampere; it could be reduced by reducing the screen current, which in our case is rather more than recommended by the manufacturer for electrometer tube application. With this larger screen current, however, we obtain an order of magnitude greater zero-stability than is obtained with the recommended value of screen current. After the input stage, a two-stage balanced amplifier is used to supply an output of one milliampere, for a nominal input of 15 to 1500 millivolts in five ranges. Ranges ordinarily may be changed without resetting the zero. Calibration voltages are built in. A simple straightforward procedure requiring less than a minute is followed after the amplifier warms up to obtain the proper balance and zero adjustments.

The stability of certain low impedance chopper-type DC amplifiers (for thermocouples, for instance) is, of course, considerably better than we obtain, but the nature of the problem with low impedance is entirely different.

Operating Instructions

The basic DC amplifier is shown in Figure 6-13 exclusive of the necessary power supplies for filament and for plate supply. The electrometer tube and the input resistor are contained in a probe which may be operated any distance up to 50 feet, or perhaps farther, from the main amplifier. Some of the operational characteristics of the amplifier and means for adjusting it are discussed in this portion of the report. When the amplifier is first turned on, the 3-gang switch marked RUN, TURN ON, DISCONNECT should be in the position shown as DISCONNECT, and the Sensitivity Switch marked (1) should be in position 6. The 3-gang switch then should be turned to the TURN ON position for about a second, which allows the filament

of the electrometer tube to be lighted before other potentials are applied. Then the switch should be turned to the position marked RUN. (The manufacturer recommends that the filament current be applied while all other potentials are zero.)

The first adjustment that is made to the amplifier is to "zero" it with the aid of the Zero adjustment (2) shown near the top of the drawing. This adjustment sets the "zero" meter current to be anything desired from +1 milliampere to -1 milliampere, and in essence adjusts the plate circuit of the two output tubes, V_4 and V_5. The next adjustment is made with the so-called Test Switch (3) in the grid circuits of the output tubes V_4 and V_5: momentarily push the switch to open the circuit. One can tell at once from the deflection of the meter whether the two grids have the same potential. Adjust Balance Control (4) in the right part of the diagram on the bleeder in order to bring the two plates of tubes V_2 and V_3, and hence the two grids of tubes V_4 and V_5, to the same potential. When all of this has been accomplished, pushing Test Switch (3) has no influence on the output meter indication, and in that situation, tubes V_2, V_3, V_4, and V_5 are in the required balanced state. The next adjustment is to turn the sensitivity switch (1) from position 6 to position 5, or perhaps 4, as may be indicated. Adjusting the control called "Bias (5)" on the bleeder near the center of the drawing adjusts the plate potential of the electrometer tube, that is, it adjusts the potential of point "X" equal to the potential of point "Y" on the bleeder. When this adjustment has been completed, there is no influence on the output meter reading when the Sensitivity Switch (1) is moved from the least sensitive range to the most sensitive one. The sensitivity control is in a bridge circuit, so that varying the sensitivity adjustment does not influence any DC potential in the amplifier. In practice, it is possible to make all these adjustments in a matter of less than a minute. After the amplifier has been warmed up for perhaps 20 minutes, the adjustments remain satisfactory for intervals of many hours.

Power Supplies and Heater Supplies for DC Amplifiers

In the snowmeter investigation of Chapter III, it was pointed out that a measurement of a snowflake consisted in part of four simultaneous records, (1) the charge carried by the flake, (2) the charge given to the dish of snow, (3) positive and (4) negative charges appearing in the air adjacent to the dish of snow. The DC amplifiers used for these four measurements were designed to have a regulated heater supply so that 150-milliampere 12-volt-heater tubes could be employed. Many interconnections were required among the amplifiers, heater supply, and the several power supplies. A diagram indicating these numerous interconnections is shown in Figure 6-17.

In the upper left-hand corner is a block showing the heater supply. In the upper center is a block showing the "TWO" power supply for amplifiers I and II used for recording the charge on the snowflake and the charge on the dish. For these two amplifiers B- was grounded. In the upper right is a block showing a pair of single power supplies, each of which is used for a single amplifier III or IV for the ion counters for which the B- is not grounded. In the lower left is a top view of the amplifiers I and II. In the lower center is a top view of a junction box. In the lower right is a block for amplifiers III and IV. A bottom view of the junction box is shown in Figure 6-18. Cables from each of the several blocks plug into the junction box. Appropriate regulated power was supplied to each chassis for B+ and for heaters. The regulated power supplies had regulated heaters in the voltage amplifier stage.

In the raindrop experiment, only one of the amplifiers was required, and to simplify some of the wiring, occasionally the chassis for amplifiers III and IV was not connected. Under these conditions the block in the right center marked C was plugged into the junction box to substitute for the heaters of the amplifiers III and IV which were not connected. The heater supply, the "TWO" supply, and the single power supplies are shown in

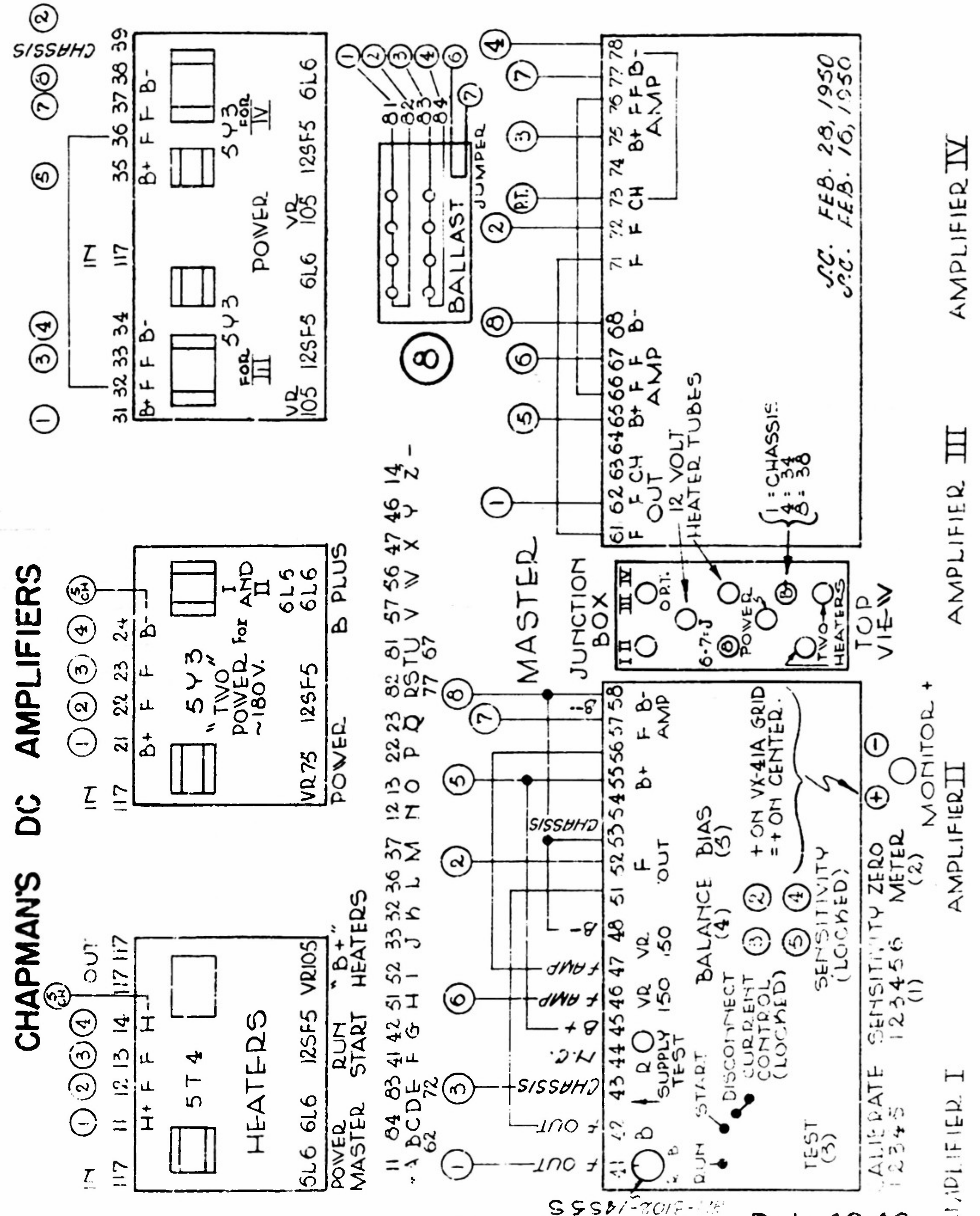


FIGURE 6-17

P-1-4040

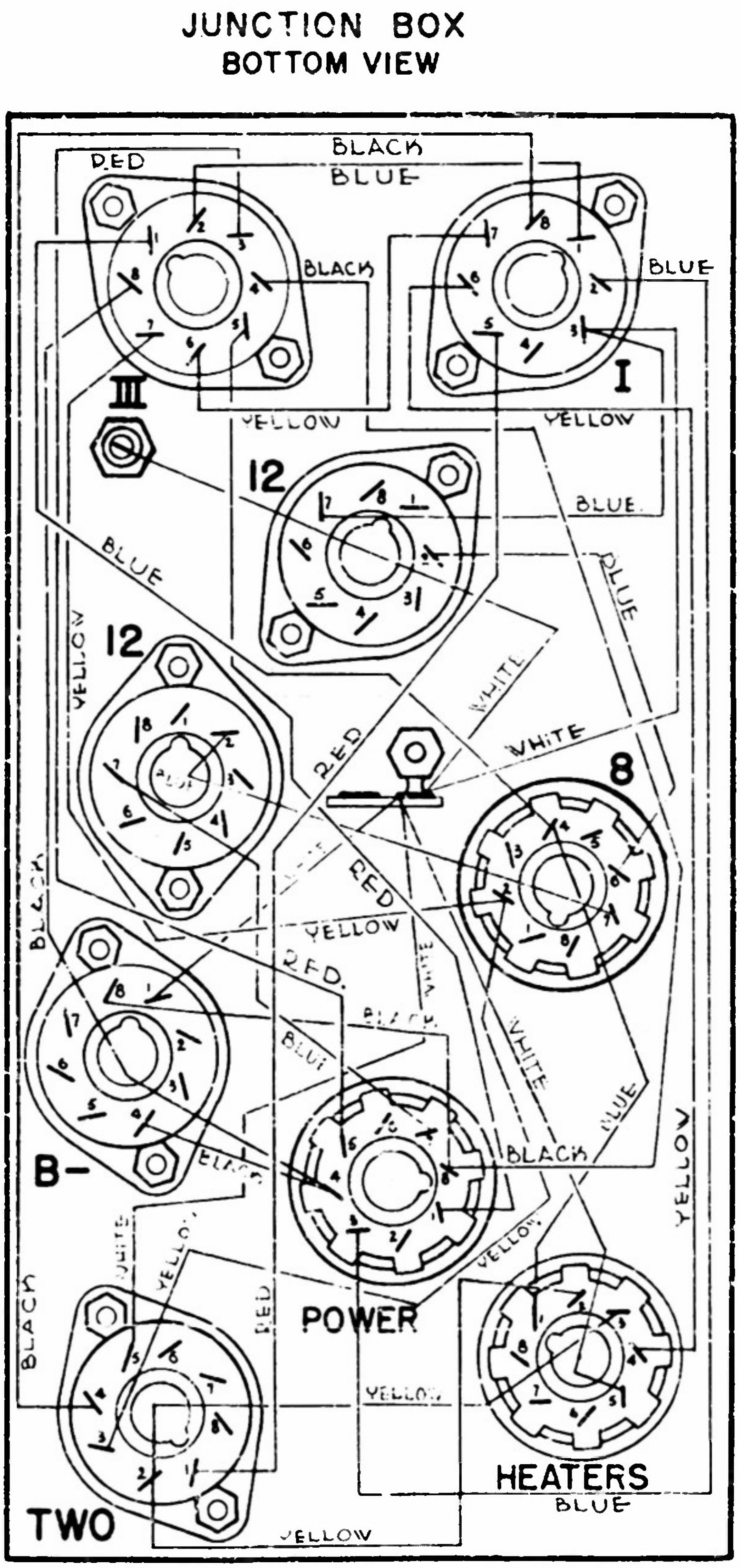

JUNCTION BOX
BOTTOM VIEW
RED
BLACK
BLUE
BLACK
BLUE
III
I
YELLOW
YELLOW
12
BLUE
BLUE
BLUE
YELLOW
12
WHITE
WHITE
RED
8
RED
YELLOW
RED
BLACK
BLACK
BLUE
WHITE
BLUE
BLACK
YELLOW
B-
BLACK
YELLOW
POWER
RED
BLACK
YELLOW
HEATERS
BLUE
TWO
YELLOW

FIGURE 6-18

Figures 6-20, 6-21, and 6-22. All are of the standard degenerative type in which the output may be adjusted to be independent of line voltage; for example in the Heater Supply, by adjusting the 1000-ohm potentiometer which is in the very bottom of diagram (ref. 18).

Two of the power supplies were capable of being adjusted to be independent of load by means of the 5-ohm rheostats shown on the Single Power Supply. Performance was about what might be expected. In one case the stabilization factor was at least 400. Since the voltage amplifier in the heater supply had its heater regulated by the heater supply, naturally the regulator could not work when it was first turned on. For this purpose a separate transformer was included to provide power for the heater of the 12SF5 during the warm-up. After warm-up the regulated current was used on the heater of the 12SF5. This circuit arrangement is shown in Figure 6-20.

Snowmeter Pulse Lengthener

In the snowmeter, when a snowflake falls through the cylinder which measures its charge by induction, the snowflake is inside the cylinder for an interval of somewhat less than 0.1 second. The amplifier connected to the cylinder produces a current surge through the recording milliammeter, lasting about 0.1 second. Since the Esterline-Angus recording milliammeters have a speed at response not adequate to follow a surge lasting less than 0.1 second, the pulses must be stretched to a time of several seconds. See Figure 6-23.

The input of the snowmeter pulse lengthener is plugged into the output of the snowmeter amplifier connected to the cylinder. Neither lead is grounded. At all times a small current flows from plate to cathode of both diodes of V_1. Thus both 0.25 mfd capacitors have an equilibrium charge on them, actually about 0.2 volt. Since the snowmeter amplifier has a balanced output, normally one expects the red lead to go positive and the blue lead to go negative, by an equal amount for a positive output pulse (actually

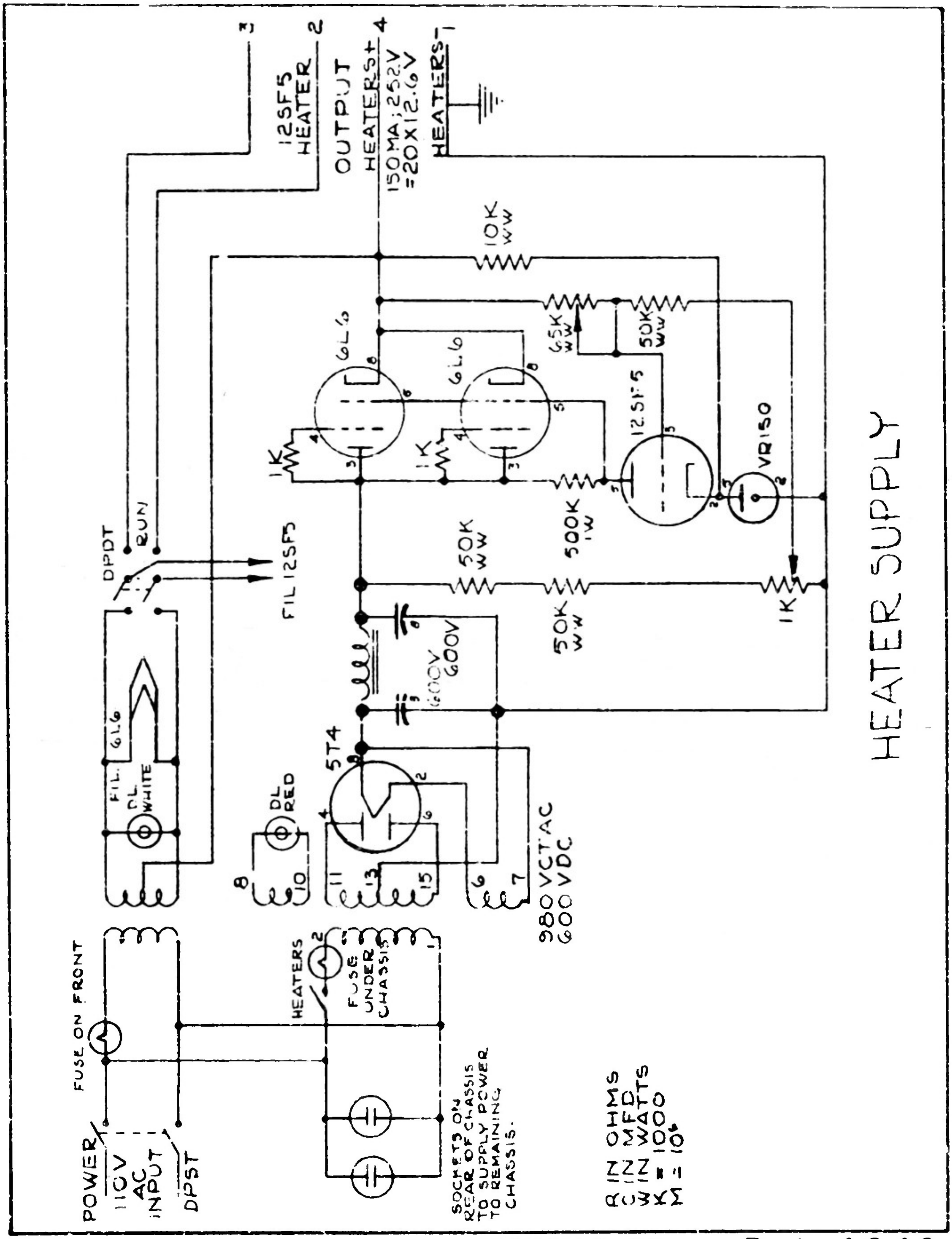


FIGURE 6-20 P-1-4042

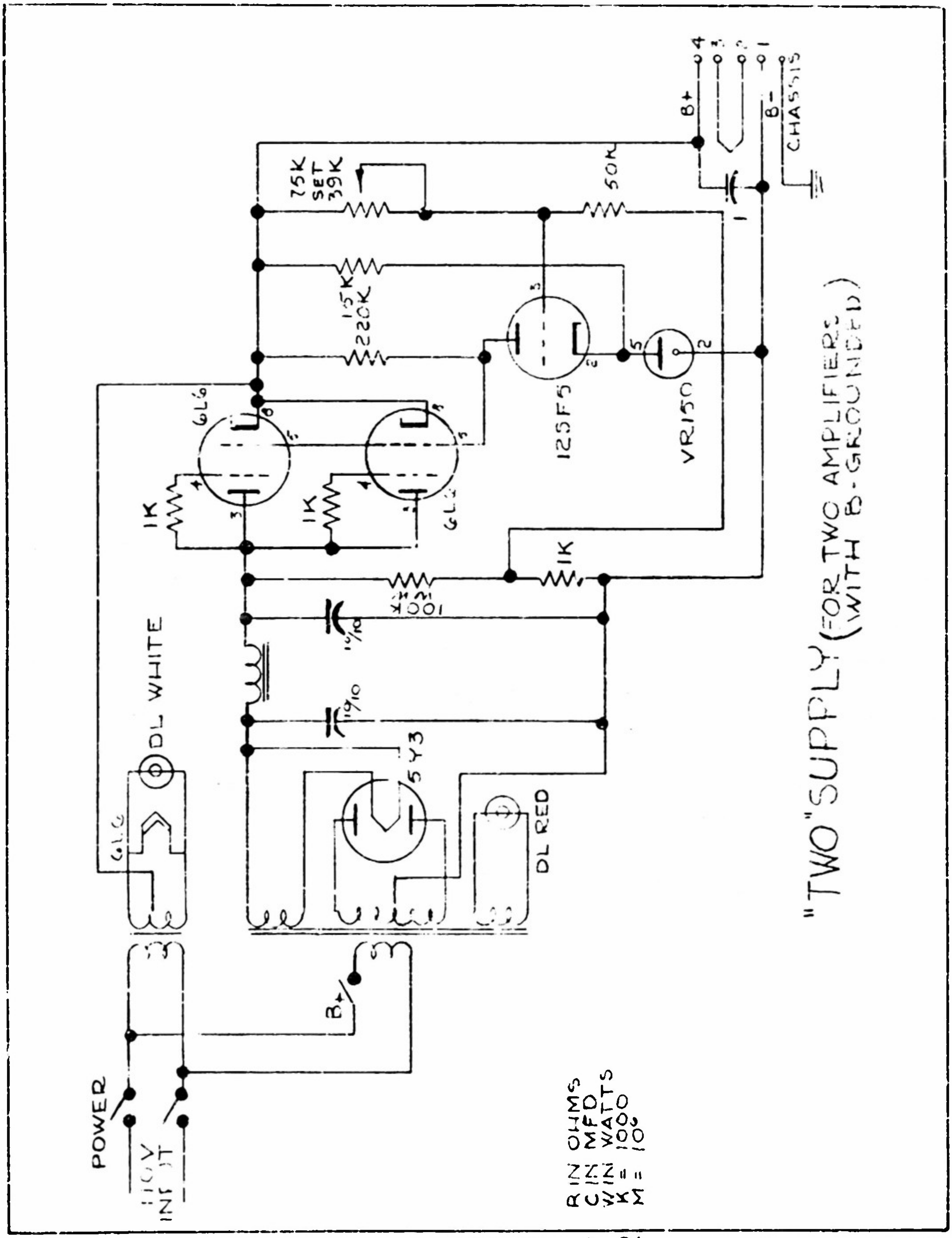


FIGURE 6-21

P-1-4043

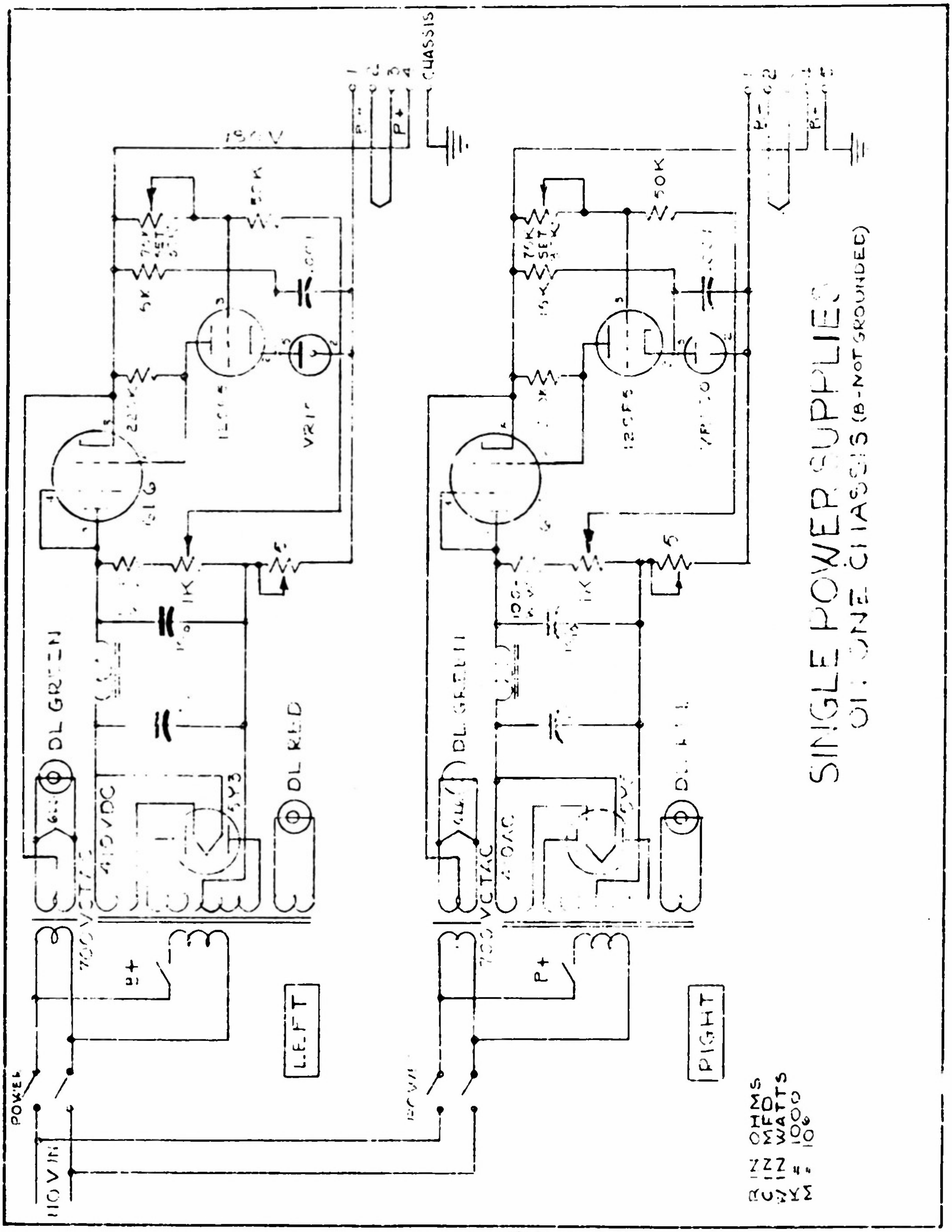

CHASSIS
P+
P-
150V
50K
1K
5Y3
6Y6
12SF5
VR150
DL GREEN
DL RED
450VDC
700VCT AC
P+
LEFT
RIGHT
POWER
110V IN
SINGLE POWER SUPPLIES
ON ONE CHASSIS (B-NOT GROUNDED)
OHMS
MFD
WATTS

FIGURE 6-22

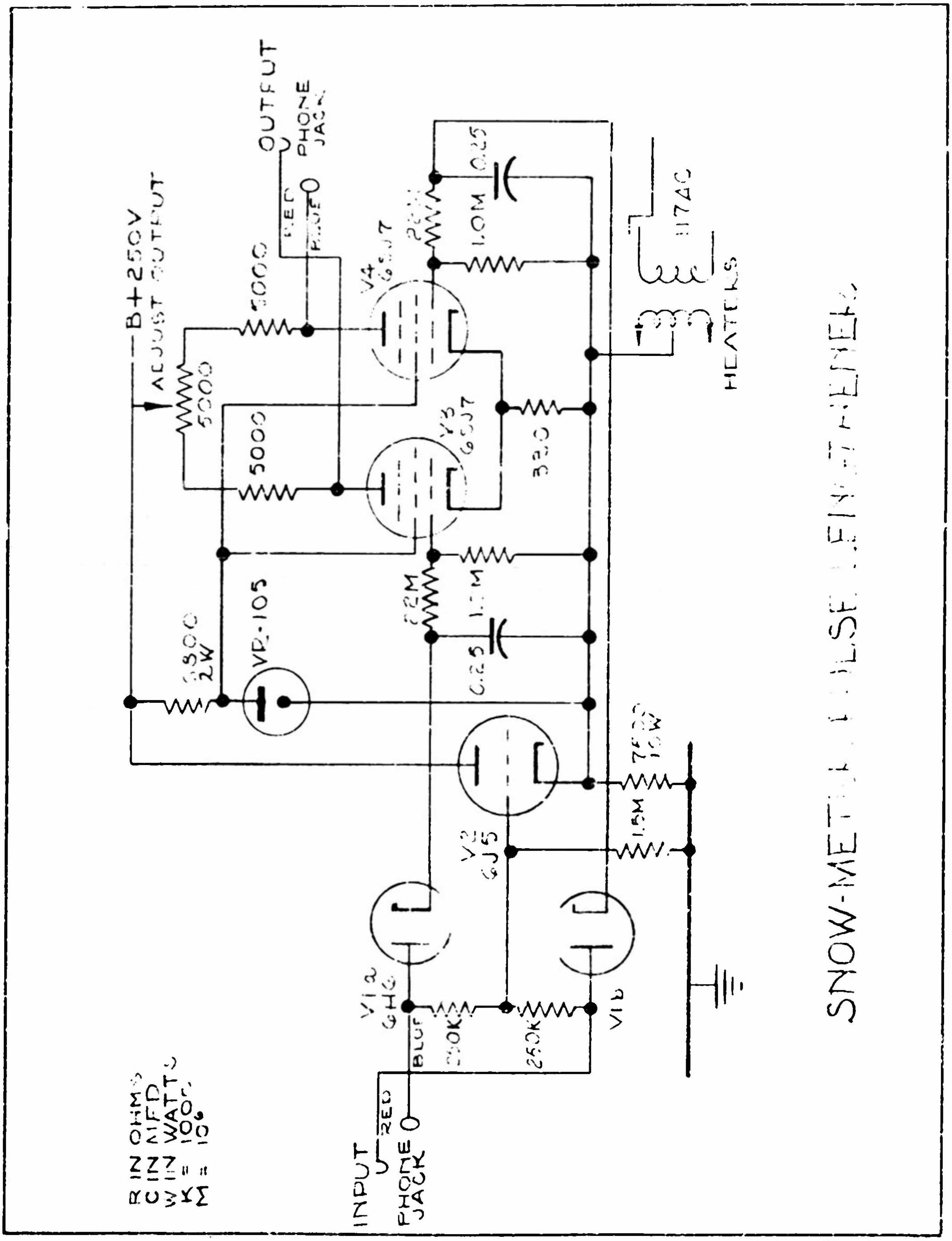


FIGURE 6-23

P-1-4045

about ±3.5 volts for 0.5 milliampere output). Irrespective of the polarity of the snowflake, one or the other lead will go positive by an amount proportional to the charge on the snowflake. As long as the change of potential is large relative to 0.2 volt, no significant error is introduced by this permanent bias. The 0.25 mfd capacitor in the lead which goes positive becomes charged. It can discharge again only through the 22 megohm and 1 megohm resistors in its grid circuit. Consequently, the pulses introduced into the output circuits of the tubes V_3 and V_4 have a time constant of approximately five seconds and are easily recorded on the Esterline-Angus recording milliammeter. The function of V_2 is to provide a reference voltage corresponding to the average input potential, so that under all circumstances there is a small conduction current through the diodes. The output circuit of the snowmeter pulse lengthener is identical with that of the snowmeter amplifier so that any pulses ordinarily accepted by the amplifier will be registered properly after passing through the pulse lengthener.

Snowmeter Trigger Circuit

As remarked in Chapter III on the snowmeter, when a snowflake fell through a ring in the snowmeter, it induced a voltage on the ring. This voltage was fed into the snowmeter trigger circuit, the output of which triggered the gaseous discharge flash tubes which gave the photographic exposures. This section describes the operation of the snowmeter trigger circuit; see Figure 6-25.

The probe used for the snowmeter trigger circuit contained a grid resistor of 3×10^{10} ohms and a VX41A electrometer tube connected as a high-mu triode with both grids tied together. The output from the electrometer tube probe was fed to V_1, a 6SJ7, acting as a voltage amplifier, from there through a gain control and thence to V_{2A}, one half of a 6SL7, which also acts as a voltage amplifier. Two outputs are taken from tube V_{2A}, one of which is fed through V_{2B} for phase inversion at unity gain so that one of the grids of tube V_3 receives a positive pulse irrespective of the

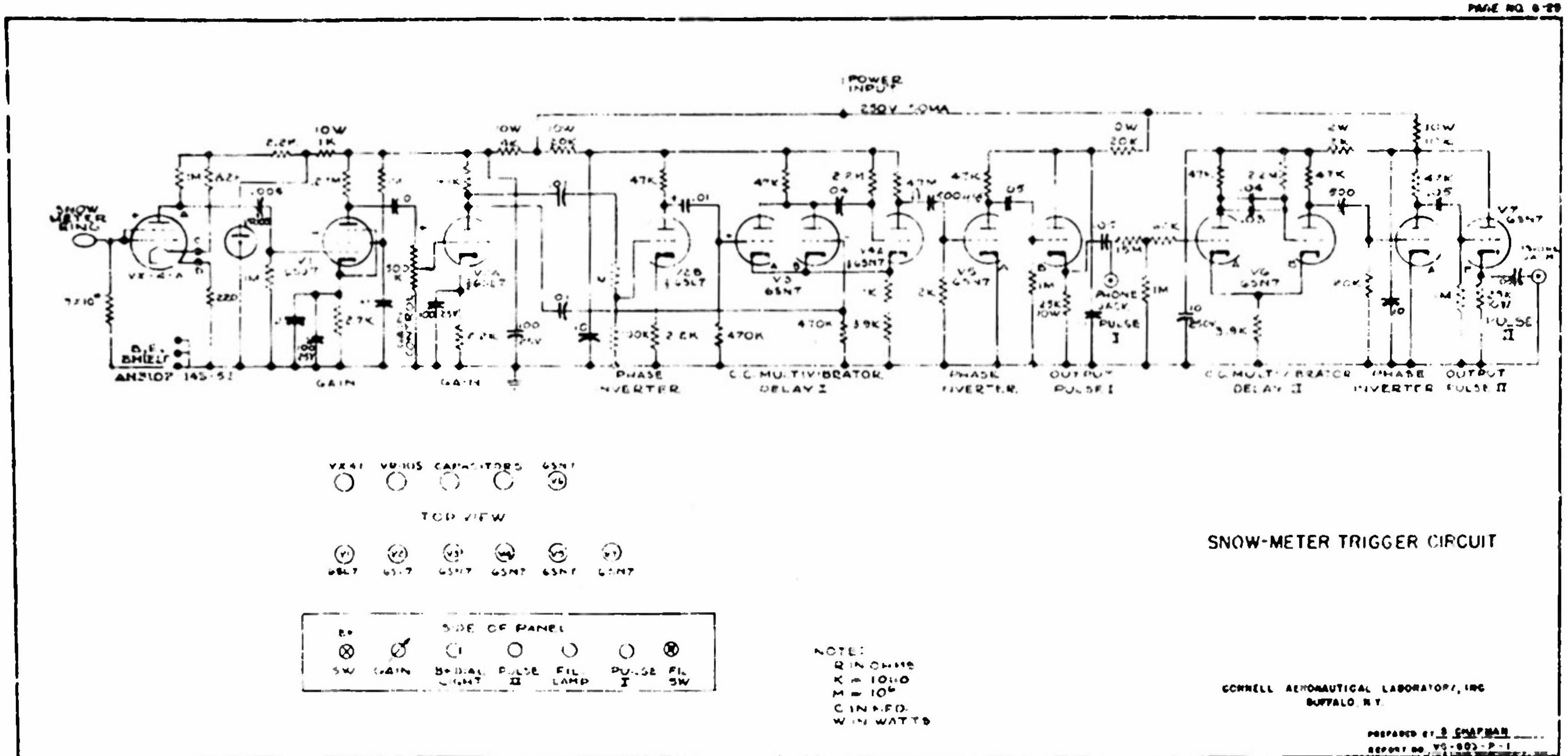


FIGURE 6-25

P-3-481

polarity of the snowflake. This half of tube V_3 ordinarily is in a non-conducting state since V_3 and tube V_{4A} combine to form a cathode coupled one-shot multivibrator (or univibrator), in which tube V_{4A} ordinarily is conducting and both halves of tube V_3 are ordinarily non-conducting.

The positive pulse on the plate of tube V_{4A} is differentiated in its plate circuit by the coupling capacitor and small grid resistor of tube V_{5A}. A negative spike is produced at the grid of tube V_{5A} at a fixed time delay after the original positive spike appears there, the positive spike being coincident with the time the snowflake goes through the ring. The positive spike produces no output in tube V_{5A} since the tube is running at zero bias, but the negative spike on the grid produces a strong positive spike in the plate circuit of V_{5A} which is transferred to V_{5B}, a cathode follower. The cathode follower transfers the delayed positive spike to the snowmeter flash circuit containing the high voltage capacitors and other equipment for energizing the flash tubes.

The flash circuit is separated from the snowmeter trigger circuit by means of long cables. Only the flash circuit itself must be maintained close to the snowmeter out in the blizzard. The output from the first flash tube trigger is used to control a second cathode coupled one-shot multivibrator, V_6, which provides another time delay. In similar fashion V_6 controls V_7 which feeds out the second pulse for operating the second flash tube. In this way, when the snowflake goes through the ring, it initiates a delay causing the first flash tube to be energized after the snowflake has fallen out of the ring into the photographic field of view, and the second flash tube to be energized about 0.02 second later while the snowflake is still in the field of view.

The snowmeter trigger circuit is supplied with power from a conventional voltage regulated power supply providing 250 volts at 50 milliamperes.

Snowmeter Flash Circuit

As mentioned in Chapter III, the measurement of a snowflake involved taking a stereoscopic photograph of it as it fell through the snowmeter. The output pulses from the snowmeter flash trigger circuits are carried by a long cable to the snowmeter flash circuit; see Figure 6-28. The flash circuit must be placed very close to the snowmeter because of the several high voltage leads which connect the snowmeter flash circuit to the snowmeter. For example, there are two spark coil leads and there are two high voltage leads carrying about 2200 volts, backed up by 25-microfarad capacitors. It is undesirable to run these leads any significant distance. A neon sign transformer provides high voltage which is rectified by an 866A rectifier. Two separate leads from the high voltage side of the rectifier are carried through dropping resistors to the two independent 25-microfarad high voltage photoflash capacitors.

Each photoflash capacitor is controlled by an independent 1D21 strobotron. When a strobotron is triggered, it discharges a 1.0 mfd capacitor through the primary of a spark coil. The high voltage output of the spark coil triggers the photoflash discharge tubes, which are General Electric Type FT-210. Pulses from the snowmeter trigger circuit are carried directly to the strobotrons which are connected so that a positive pulse on the so-called outer grid discharges the strobotron, energizes the spark coil and triggers the flash tubes. Auxiliary switches may be used to discharge the strobotrons and hence the flash tubes when desired. A milliammeter connected to one of the high voltage leads indicates when the capacitors have been charged fully.

Corona Current Logarithmic Amplifiers

In the study of the earth's electric field during snow storms, it was necessary to measure the corona current to a corona point exposed 54 feet above the ground. The current range to be covered was of the order of 1 to 100 microamperes of both polarities. Because of the wide range of

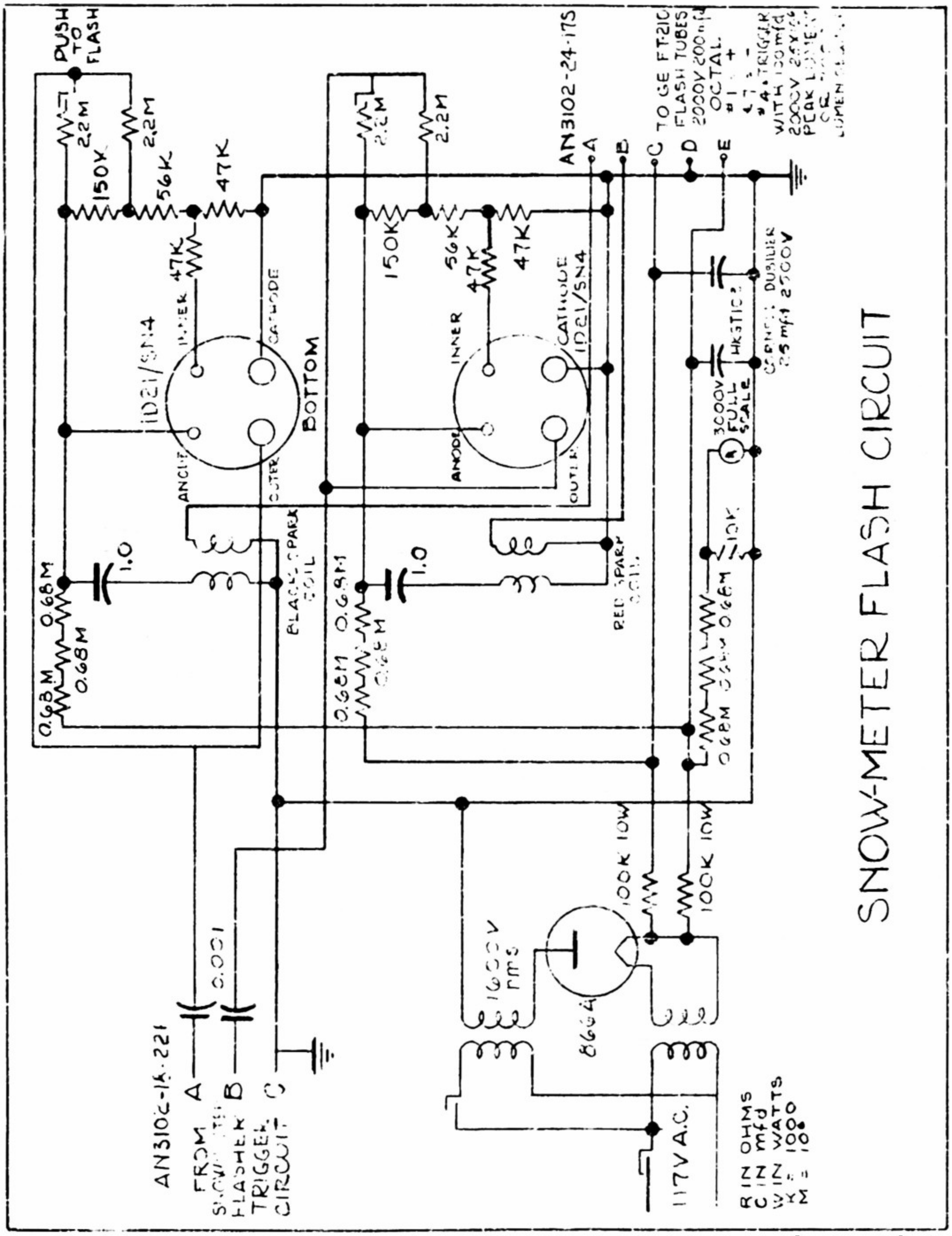

SNOW-METER FLASH CIRCUIT
PUSH TO FLASH
AN3102-24-17S
TO GE FT-210 FLASH TUBES
1D21/SN4
BOTTOM
CATHODE
INNER
ANODE
OUTER
BLACK SPARK COIL
RED SPARK COIL
150K
56K
47K
2.2M
0.68M
1.0
0.001
100K 10W
1600V rms
866A
117V A.C.
3000V FULL SCALE
10K
AN3102-1A-22S
FROM SNOW-METER FLASHER TRIGGER CIRCUIT
A
B
C
D
E

FIGURE 6-28

current to be measured, it seemed desirable to use some non-linear device.

The corona current logarithmic amplifier Model 1 is shown in Figure 6-30 together with its calibration curve. This amplifier made use of the non-linear characteristics of the remote cut-off pentodes 6SK7 connected as triodes. While the amplifier behaved more or less as hoped, its output relation was rather curved whether plotted linearly or logarithmically. As mentioned elsewhere, its output impedance was very low, and the recording meter was severely over-damped.

Following the idea of using pentodes with all grids tied together, (ref. 23) the corona current logarithmic amplifier Model 2 shown in Figure 6-31 was constructed. The performance of this amplifier was substantially better than that of Model 1, but in fact was still disappointing, since replacing tubes markedly altered the calibration.

It appeared that by changing the grid circuits of the 12SJ7 pentodes from constant voltage (ref. 23) to constant current, and by modifying the heater circuits, significant improvements in operation would be achieved. The corona current logarithmic amplifier Model 3 (Figure 6-31a) was constructed with these ideas in mind, and served the project during the entire time records were made at one of the stations (2343 Kensington Avenue).

While Model 3 was satisfactory, an improved model was needed for the Laboratory station. It was felt that Model 3 was more complicated than necessary. Accordingly the bipolar logarithmic amplifier discussed in the next section was designed. Its input-output relationship was more linear than any earlier model. The performance of the bipolar logarithmic amplifier was entirely satisfactory. So far as we are aware, these are the first logarithmic amplifiers dealing with both polarities of current.

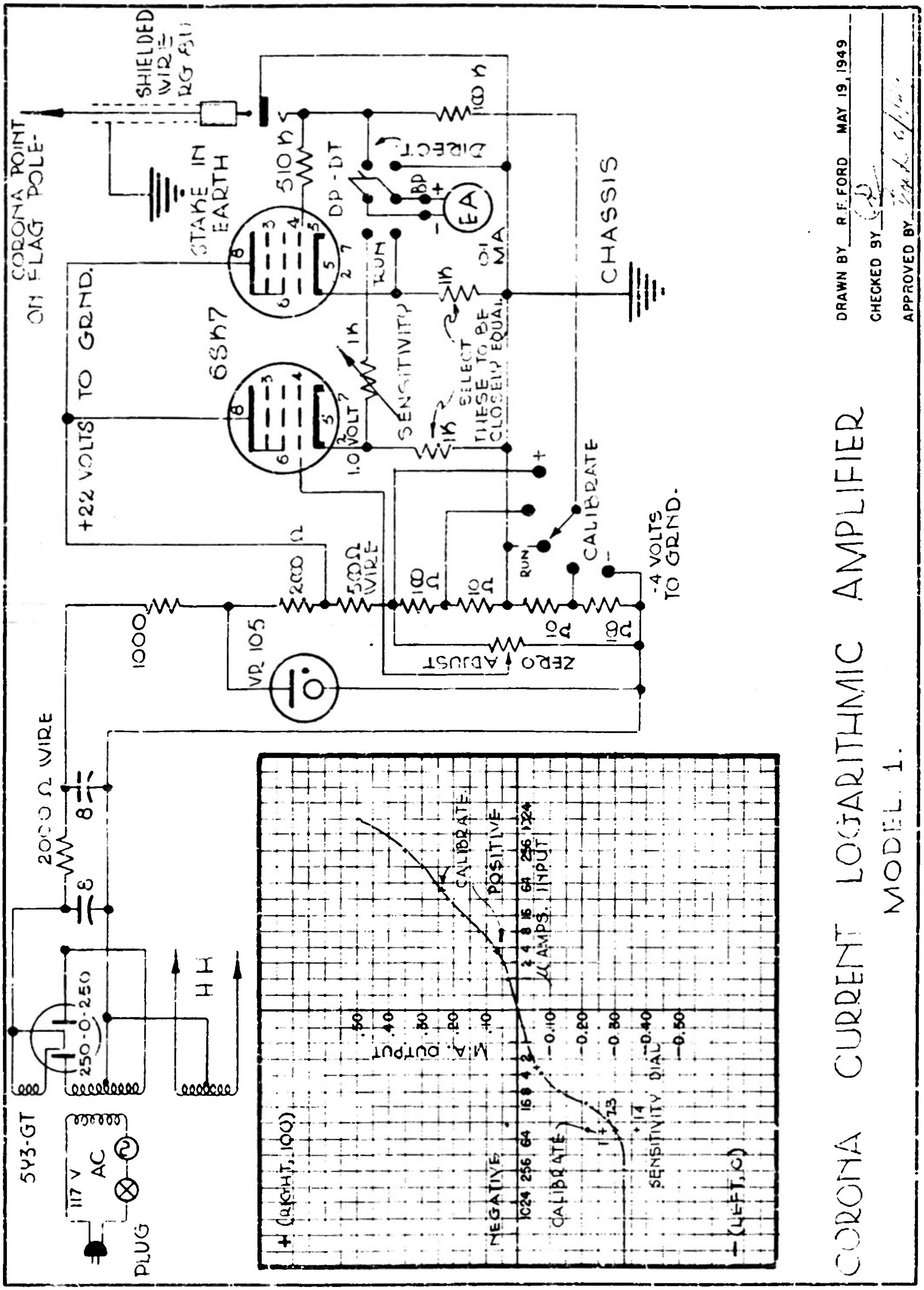
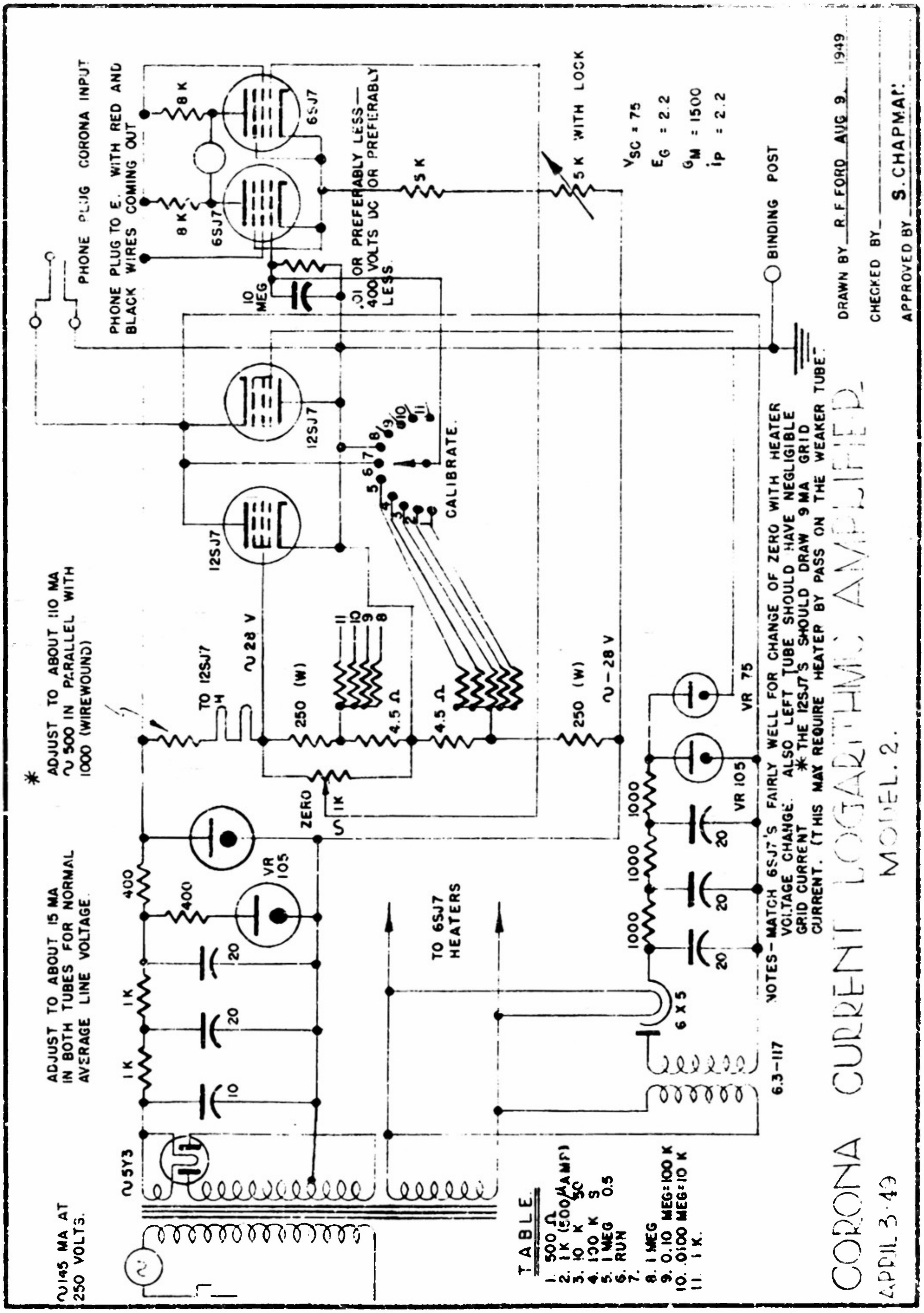

CORONA CURRENT LOGARITHMIC AMPLIFIER
MODEL 1.
DRAWN BY R.F. FORD MAY 19, 1949
CHECKED BY
APPROVED BY
CORONA POINT ON FLAG POLE
SHIELDED WIRE RG 8/U
STAKE IN EARTH
CHASSIS
+22 VOLTS TO GRND.
-4 VOLTS TO GRND.
6SK7
5Y3-GT
VR 105
117 V AC
PLUG
2000 Ω WIRE
SENSITIVITY
SELECT THESE TO BE CLOSELY EQUAL
DIRECT
DP-DT
RUN
CALIBRATE
ZERO ADJUST
M.A. OUTPUT
μ AMPS. INPUT
NEGATIVE
POSITIVE
SENSITIVITY DIAL
+ (RIGHT, 100)
- (LEFT, 0)

FIGURE 6-30



CORONA CURRENT LOGARITHMIC AMPLIFIER
MODEL 2.
APRIL 3 49
DRAWN BY R.F. FORD AUG 9 1949
CHECKED BY
APPROVED BY S. CHAPMAN
PHONE PLUG CORONA INPUT
PHONE PLUG TO E. WITH RED AND BLACK WIRES COMING OUT
8 K
8 K
6SJ7
6SJ7
5 K
5 K WITH LOCK
$V_{SC} = 75$
$E_G = 2.2$
$G_M = 1500$
$i_P = 2.2$
10 MEG
.01 OR PREFERABLY LESS—400 VOLTS DC OR PREFERABLY LESS
BINDING POST
12SJ7
12SJ7
CALIBRATE
∿145 MA AT 250 VOLTS
∿5Y3
10
20
20
1 K
1 K
400
400
VR 105
VR 105
VR 75
ADJUST TO ABOUT 15 MA IN BOTH TUBES FOR NORMAL AVERAGE LINE VOLTAGE
* ADJUST TO ABOUT 110 MA ∿500 IN PARALLEL WITH 1000 (WIREWOUND)
TO 12SJ7 H
∿28 V
250 (W)
4.5 Ω
4.5 Ω
250 (W)
∿-28 V
ZERO
1K
TO 6SJ7 HEATERS
6 X 5
6.3-117
1000
1000
1000
20
20
20
NOTES - MATCH 6SJ7'S FAIRLY WELL FOR CHANGE OF ZERO WITH HEATER VOLTAGE CHANGE. ALSO LEFT TUBE SHOULD HAVE NEGLIGIBLE GRID CURRENT. * THE 12SJ7'S SHOULD DRAW 9 MA GRID CURRENT. (THIS MAY REQUIRE HEATER BY PASS ON THE WEAKER TUBE)
TABLE
1. 500 Ω
2. 1K (500 AMP)
3. 10 K
4. 100 K
5. 1 MEG
6. RUN
7.
8. 1 MEG
9. 0.10 MEG; 100 K
10. 0.0100 MEG; 10 K
11. 1 K.

FIGURE 6-31

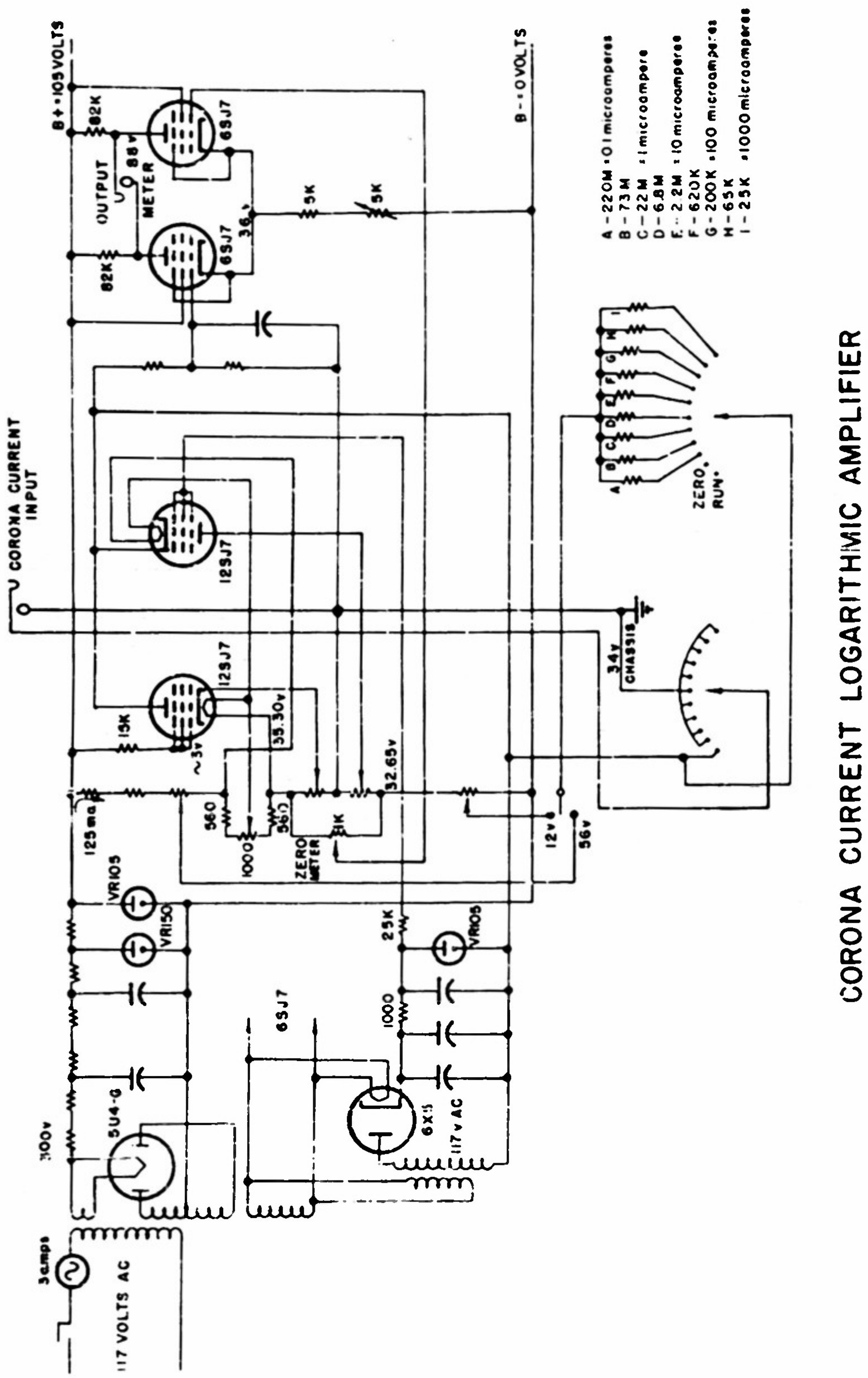

CORONA CURRENT LOGARITHMIC AMPLIFIER
MODEL 3
B+ =105 VOLTS
B- = 0 VOLTS
CORONA CURRENT INPUT
OUTPUT METER
A - 220M = .01 microamperes
B - 73M
C - 22M = 1 microampere
D - 6.8M
E - 2.2M = 10 microamperes
F - 620K
G - 200K = 100 microamperes
H - 65K
I - 25K = 1000 microamperes
ZERO
RUN
34v
CHASSIS
6SJ7
12SJ7
82K
88v
36v
5K
13K
35.30v
32.65v
~3v
125 ma
560
1000
ZERO METER
1K
12v
56v
VR105
VR150
25K
5U4-G
6X5
300v
117 v AC
3amps
117 VOLTS AC

FIGURE 6-31a

Bipolar Logarithmic Amplifier*

In a study of the earth's electric field during snow storms and thunderstorms, it was necessary to measure the corona current to a corona point exposed 54 feet above the ground. The current range to be covered was approximately from 10^{-7} ampere to 10^{-3} ampere with either polarity. Because of the wide range of current to be measured, a logarithmic device was needed.

The logarithmic relationship between retarding voltage and current in a temperature-limited diode having a pure metal cathode has been known at least since 1914 (ref. 1)** and various experimenters have constructed logarithmic amplifiers using this principle, or variations of it (refs. 2-6). The theory of such tubes has been discussed in several places (refs. 7-9). Ordinarily, only a single polarity of current has been considered. A particularly interesting report (ref. 5) is given indicating that under proper conditions, for one polarity the 9004 Acorn diode has a logarithmic range of 10^9. For the present application, however, it was necessary to deal with both polarities. After we tried several other circuits with unsatisfactory results, the one given in detail in Figure 6-33 was constructed. As shown in Figure 6-34B, it consists essentially of two biased diodes back to back, shunted by a resistor R, the output of which is fed to a simple DC amplifier, which in turn feeds a -0.5 to 0 to +0.5 milliampere Esterline-Angus recorder.

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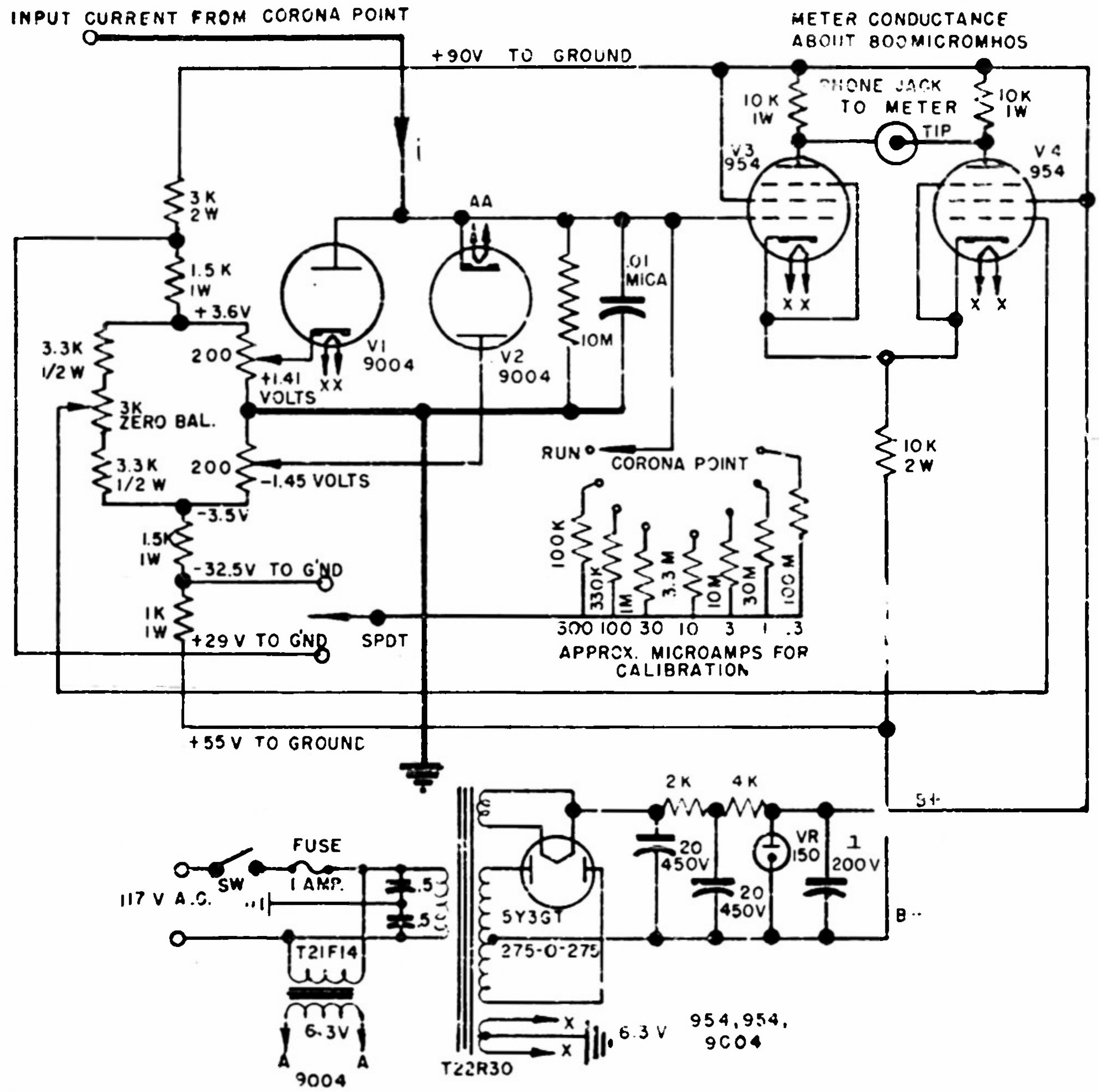
*The work in this section was conducted on internal research funds provided by Cornell Aeronautical Laboratory. At the time no ONR funds were available because of contractual complications. The bipolar logarithmic amplifier has applications beyond the scope of this report. It is included here because this is one of the applications, and the amplifier described in this section is superior to any other described in the literature on problems of atmospheric electricity.

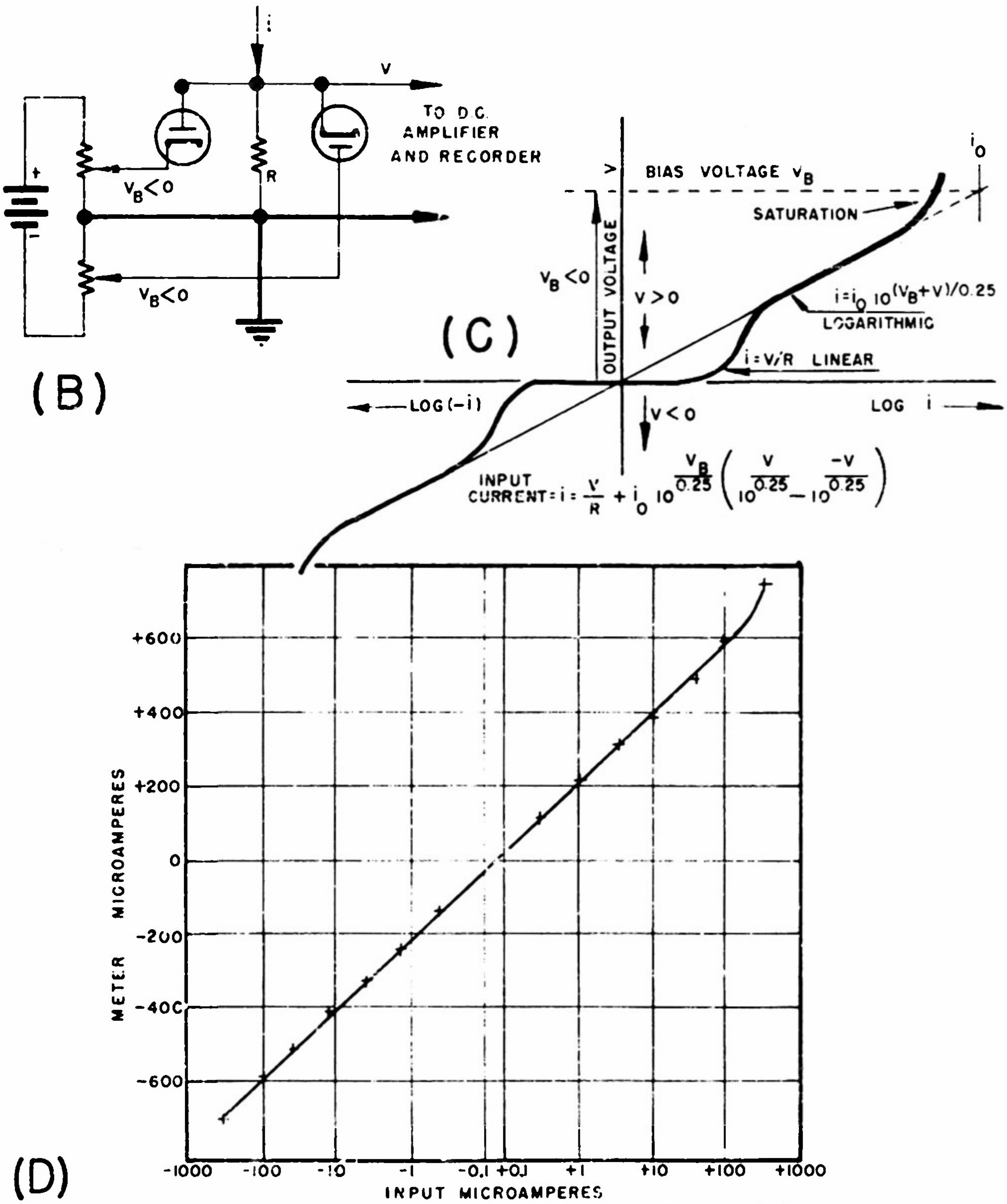
**For this section only, references are given at the end of the section.



R IN OHMS
C IN MFD
W IN WATTS
K = 1000
M = 10^6

BIPOLAR LOGARITHMIC AMPLIFIER (A)

FIGURE 6-33



CALIBRATION FOR BIPOLAR LOGARITHMIC AMPLIFIER (A)

BIPOLAR LOGARITHMIC AMPLIFIER

FIGURE 6-34

P-1-4047

In the case where the anode of a diode is biased negatively relative to the cathode (even when the cathode is not a pure metal), the relationship between diode current i and retarding potential $-V$ may be given by

$$i = i_o \varepsilon^{-Ve/kT}$$

where
- e is the electron charge
- k is Boltzmann's constant
- T is the absolute temperature of the cathode
- $\varepsilon = 2.718+$
- i_o is a constant depending upon geometry and other factors.

In practice, this equation becomes invalid at various parts of the range because of effects of positive ion current in the tube, shunting leakage or circuit resistance, currents to grids of following stages, saturation of the diode leading to a space charge situation (at the high end of the current range), photoelectric emission from the anode or grid, rectification from AC pickup in high impedance leads, and heater leakage or rectification, etc.... In fact, in the bipolar case where two diodes are required, it is virtually impossible to operate the circuit without a separate filament transformer for the heater of the diode with the high impedance cathode.

With the temperatures of typical cathodes, the quantity e/KT corresponds to from 4 to 5 decades per volt. In Figure 6-34C the output voltage of the two diodes back to back is sketched in qualitative fashion relative to the logarithm of the current. Naturally, no logarithmic function goes through zero. Whether or not there is a shunting resistor, there must be a linear region near zero so that the actual relationship is of the form of a hyperbolic sine ($2 \sinh x = e^x - e^{-x}$, which is a function that is linear near zero and logarithmic far from zero).

The location of the region of transition from a logarithmic to a linear relationship may be changed by adjusting the shunting resistor R or by adjusting the biases applied to the two diodes. When the biases are fairly

large, the location of the linear range is determined by the shunting resistance R. Figure 6-34C has been drawn for this case.

The circuit as constructed actually had a logarithmic range from 3×10^{-9} to 3×10^{-4} amperes for both polarities.* The biases were adjusted as shown in Figure 6-33 to yield the calibration given in Figure 6-34D. Changing the biases, of course, changes the circulating current through the diodes. On the assumption that the cathode temperature is proper, the relationship between current i and output voltage V is given as indicated in Figure 6-34C as

$$i = \frac{V}{R} + i_o \, 10^{\frac{V_B}{0.25}} \left(10^{\frac{V}{0.25}} - 10^{\frac{-V}{0.25}} \right)$$

where i_o is a constant and V_B is the bias voltage.

The unique feature of the amplifier is its ability to adjust the bipolar-logarithmic-to-linear transition to any desired magnitude of current (within limits of course), the effect being to "swallow" the middle section of the logarithmic characteristic of output voltage versus input current (where it becomes linear) to whatever extent desired. Thus the logarithmic range can cover $\pm 10^{-6}$ to $\pm 10^{-4}$ amperes or $\pm 10^{-7}$ to $\pm 10^{-4}$ amperes, or $\pm 10^{-8}$ to $\pm 10^{-4}$ amperes, as desired.

The practical amplifier shown in Figure 6-33 has several built-in calibration points. The meter current is about 800 microamperes per volt input, corresponding to about 200 microamperes per decade of corona current. The equipment has been in service for about 15 months, and providing the tubes are replaced after their rated life, it behaves very well.

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*Unquestionably the ranges could have been extended to smaller currents, but since the smallest currents which could be measured already were less than required for this application, further development was not undertaken. We have also operated the Victoreen 5800/VX-41A between 3×10^{-14} and 3×10^{-8} amperes as a logarithmic diode without reaching the ends of the range, and also the Raytheon CK5886/CK571 over 7 decades.

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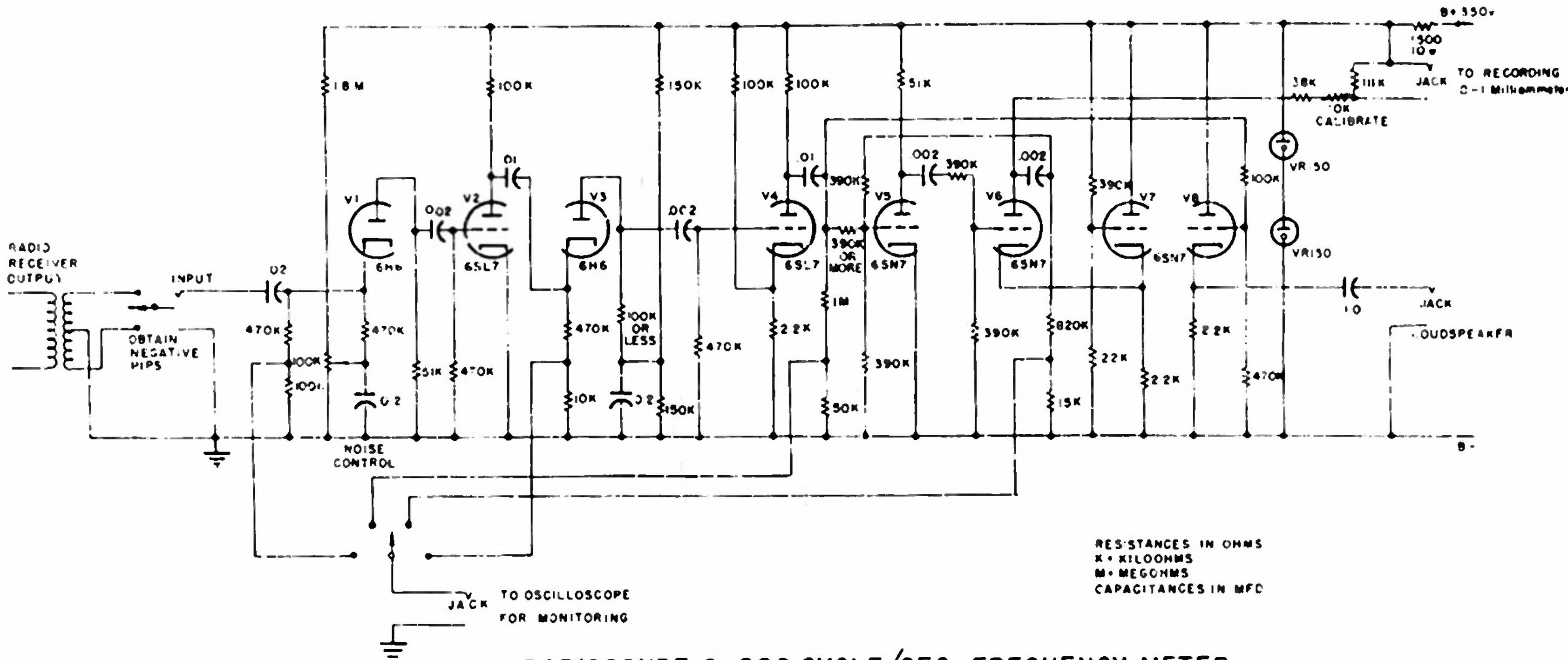
Radiosonde Frequency Meter

Basically the circuit of the radiosonde frequency meter was as follows: (see Figure 6-39). The radiosonde signal from the AN/APR-4 consisted of negative pips. It was fed into a biased diode V1 so that only negative signals of magnitude greater than an adjustable bias voltage were passed by the diode. In this way a large fraction of the background and noise could be eliminated from the signal. After one stage of amplification in V2 the signal went through another biased diode V3 which would saturate if the signals were stronger than a preassigned value necessary to render conducting the following tube V4 which ordinarily was biased beyond cut-off. When this tube V4 was made conducting, it triggered the biased one-shot multivibrator

V5-V6. For each pip of the radiosonde signal, the one-shot multivibrator fired once causing a certain charge to flow through the recording milliammeter.

Tube V7 provides a bias for the one-shot multivibrator V5-V6. Tube V8 is used as a speaker amplifier, so that the pips from the radiosonde could be heard. At various points in the circuit signal voltages were taken off in a way so that they could be switched to the oscilloscope for visual monitoring. The oscilloscope proved to be very helpful for tuning in weak signals of the pulse-modulated radiosonde. It also was useful to monitor strong signals to prevent saturation of the frequency meter by severe overload.

The input noise control was adjusted from time to time, so that as much of the background noise as desired could be cut out from the signal. Satisfactory frequency records could be made at any time when the signal was more than about 3 db above the background "grass", or background noise. The frequency meter output resistance was adjusted to be slightly less than the critical damping resistance of the Esterline Angus meters in order to provide maximum speed of response without significant overshoot. Linearity was within 1%.



RESISTANCES IN OHMS
K = KILOOHMS
M = MEGOHMS
CAPACITANCES IN MFD

RADIOSONDE 0-200 CYCLE/SEC. FREQUENCY METER

FIGURE NO 6-39

VII. SUMMARY

Note: This chapter is a summary of material appearing in the report. Nothing is discussed in this chapter which has not been referred to previously.

In Chapter I the objective of this project is stated to have been to investigate certain mechanisms that may be effective in generation of electrical charge in thunderclouds, and to conduct some auxiliary experiments. These experiments concerned (1) electrification generated upon disruption of raindrops, (2) electrification generated upon impact of snow crystals on one another, (3) investigation by means of corona points of the earth's electric field at the ground during blizzards, and (4) investigation by means of specially modified radiosondes of the earth's electric field in the upper air during blizzards.

In Chapter II it is pointed out that Simpson's early measurements of breaking drop electrification were conducted in such a way that negative charge in the air would not have been distinguished from a mixture of positive and negative with the latter predominating. There were reasons for believing that breaking-rain-drop electrification might be greater than had been supposed. Accordingly a vertical wind tunnel about 13 feet high, and of cross section 4x4 inches tapering to 4x8 inches was used so that drops could be introduced into the tapered section and remain suspended for times up to half an hour by a vertical air blast of about 8 meters per second.

The wind tunnel was constructed in such a way that some resolution was possible of the mobility of the electrified particles. The top of the tapered section opened into another 4x8 inch tunnel making the over-all cross section 8x8 inches in the measuring section. Charge liberated on disruption of drops was driven horizontally to an electrode by a potential difference of up to 12,500 volts, and was measured by a recording amplifier. The voltage source and recording system were compensated for supply line

changes. Typical deflections corresponded to one volt in the 43 micromicro-farads capacitance shunted by a resistance of 10^{11} ohms.

The magnitude of electrification depends critically on the method of disruption. Smooth coalescense of two drops of ordinary distilled water in an electric-field-free region followed by their break-up into a few large fragments releases very little electrification into the air, less than 10^{-13} coulombs per broken drop. Conversely when the water drops of 4 millimeters diameter were allowed to fall for a distance of 5 centimeters in a region protected from the vertical up-draft, so that they acquired a speed of about one meter per second before striking the updraft, they appeared to be shattered by the up-draft, and yielded electrification which varied greatly from drop to drop (from zero, or less than the least count of the amplifier, which was 10^{-13} coulombs per drop, to 5×10^{-10} coulombs per drop). To get significant results, therefore, runs were made of from 15 to 65 drops for a given situation. The average total charge for particles having mobilities greater than 0.25 cm/sec per volt/cm was 1.0×10^{-10} coulombs per broken drop. It is important that almost equal quantities of <u>both</u> positive and negative electrification were found in this range.

Some experiments were made on 5×10^{-4} molal hydrochloric acid, potassium hydroxide, and potassium chloride, but the results were not much different from water, although in all cases the electrification appeared to be somewhat greater. The mobility spectra did not have sufficient detail to permit drawing any significant conclusion.

Because of the importance of the ice-water phase-changes in thunderclouds, as implied by the investigations of Workman and of Kuettner, one run was made on drops 3 millimeters in diameter which had been supercooled to a temperature of -6°C by bringing in cold winter air from out-of-doors for the air stream of the wind tunnel. The supercooled drops could not be disrupted by the 5-cm-free-fall method since they would freeze on the inlet. Accordingly warm drops were introduced and allowed to float for 20 seconds

or longer until they became supercooled. Then they were disrupted by a momentary puff of compressed air from twin jets on either side of the tapered section of the tunnel. Under the same conditions another run was made with drops at 14°C. The supercooled drops yielded average total charges of 6.8×10^{-12} coulombs per drop, while the warm drops gave 6.3×10^{-12} coulombs per drop. The conclusion is that in this one set of conditions, supercooling the drops appears to have no significant effect. The data should be considered suggestive rather than definitive on this point. Visual inspection indicated that the drops had not been shattered as completely as in the 5-cm-free-fall method.

In general, magnitudes of electrification are related to the degree of break-up of the drops as judged visually. The magnitudes of charge obtained are sufficient to account for either a negligible fraction of thundercloud electrification, or all of it, depending upon the degree of disruption in the thundercloud.

An elementary model of thundercloud charge generation is worked out, based on the assumption that there is considerable micro-turbulence over distances of inches or feet in the cloud, resulting in frequent coalescence and shattering of drops. Frequency of coalescence is determined in a manner analogous to the determination of mean free path in kinetic theory of gases and frequency of molecular impact.

For a charge of 100×10^{-12} coulombs per drop (which is what was observed in these tests), in a cloud having an active volume of ten cubic kilometers containing 5 grams of liquid rain-drops per cubic meter, if the drops are taken to have a diameter of 4 millimeters, and a random speed of 4.4 meters per second, they will coalesce and break every 21 seconds after traveling 94 meters. The cloud referred to contains water equivalent to a precipitation of one centimeter of water in the active depth of two kilometers. If the charging rate in the cloud were constant, then one 25-coulomb lightning flash could be generated every seven seconds.

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PREPARED BY Seville Chapman REPORT NO. VC-603-P-1

While the Wilson theory of charge separation originally was based on the supposition that atmospheric ionization would provide sufficient electrification, a calculation shows that the air in the entire active region would have to be replaced every 2.5 seconds in order to provide adequate ionization. If the breaking-drop ionization of both polarities is separated by the Wilson polarization mechanism, however, by preferential capture of positive charges on the heavier drops, a means is provided for the build-up of the thundercloud field qualitatively in accordance with the facts.

The present theory is weak in that it does not account for the initiation of the electrification process in a large building cumulus cloud. The theory also requires considerable microturbulence in the cloud. It may be that the ice-water phase transition can account for initiation of electrification, (or of course, it may be responsible for a great deal more than that).

Even if there is insufficient microturbulence for charge generation as postulated, it must be remembered that the raindrops in the normal earth's electric field plus thundercloud electric field will be polarized. For a spherical drop 4 millimeters in diameter in a field of 3000 volts per centimeter, the total induced charge on the surface of the drop is 100×10^{-12} coulombs. This rather large charge associated with limiting values of electric field strength of about 3000 volts per centimeter, by coincidence, is just equal to the datum for breaking drops in a field free region. If the drops are drawn out in breaking, the same charge will be achieved for a smaller field. When these drops are broken, a substantial part of this charge may be separated.

It is concluded in the text that breaking-drop processes cannot be ruled out as thundercloud mechanisms on the basis of alleged inability to generate sufficient charge.

In Chapter III it is pointed out that snow crystals are an important constituent of at least the upper parts of thunderclouds. Data on snow electrification are lacking, and efforts were made to measure the

electrification when one snowflake falling in a natural snowstorm struck another snowflake on a dish of snow. Stereoscopic photographs were made of the snowflake as it fell through a device referred to as the snowmeter. The charge on the falling flake was measured by induction without touching it as it fell through a cylinder connected to a recording amplifier. The dish of snow was connected to a second recording amplifier. Two fans sucked air past the dish through two electrometer chambers or so-called ion-counters, one positive, and one negative, where the charge liberated in the air on impact of the snowflake could be observed. Thus one could observe the charge on the flake, the charge given to the dish (which might be expected to differ from that of the flakes), and charges of both polarities liberated in the air, perhaps as small spicules of a flake were broken on impact.

The electronic equipment required for the four recording amplifiers, and for the synchronized discharge flash-lamps for the photography, was rather extensive.

For reasons beyond our control, the project was reduced to inactivity throughout most of the snow season. For the remainder of the seasons experimental misfortunes prevented acquisition of useful data on the two occasions when efforts were made to use the equipment. The equipment functioned entirely satisfactorily.

It is emphasized that since there are several distinct snow types, attempts to measure snow electrification may be meaningless unless specific efforts are made to identify the particular snow type involved such as by photography or by replicas.

In Chapter IV it is pointed out that information on the earth's electric field during blizzards was very scarce or almost non-existent. While the corona current to a point exposed from a high place like the top of a flagpole is only a semi-quantitative measure of the electric field, and while a corona point is insufficiently sensitive to work in fair weather or mildly disturbed weather, it gives a considerable indication during strongly

disturbed weather such as blizzards. Two corona points, 54 feet and 32 feet high, were operated with recording amplifiers over an interval of 22 months. Many storms were observed.

Most of the time the corona current is zero, especially in fair weather. In disturbed weather, and especially when precipitation is falling, the electric field fluctuates markedly over an interval of as little as five seconds. In one case the field varied from -10 to +10 times normal within a minute. Even in the absence of lightning, changes of polarity from positive to negative to positive again within an interval of a few minutes are common. Storms seem to have rather typical electrical patterns. Rain and snow are easily distinguished from lightning, and occasionally from each other. Corona currents commonly are of the order of 10 microamperes. The corona current becomes unsteady, and is useless as an indication of field at currents less than 0.1 microampere. Calibration is discussed in the next chapter.

Records with marked asymmetry-in-time are common, indicating the existence of horizontal inhomogeneities in the electrical structure of the cloud. There is a remarkable coherence-in-time between records made at the two stations 1.7 miles apart, irrespective of wind direction, indicating that the agencies responsible for electrification have dimension measured in miles. Several examples of corona records are shown.

A summary of all weather situations discussed in the report is included.

In Chapter V on radiosonding, the program to investigate the vertical extent of snowstorm electrification is discussed. Standard radiosondes were modified to measure the vertical component of the earth's electric field by means of a measurement of the corona current between two corona points carried aloft. One point was three feet above the radiosonde, and the other point was carried at the end of a trailing conducting string often several hundred feet long. It would have been dangerous to use a trailing wire of that length in a well-populated region where there are many electric wires. The conducting string had a resistance of 0.5 megohm per foot, negligible for atmospheric electrical measurements, but adequate for protection.

The corona current flowed through the grid resistor of a buffer amplifier added to the radiosonde. This amplifier modulated the radiosonde. The signal was received on the ground and recorded with the aid of considerable electronic equipment. The radiosonde was equipped with special aneroid-operated baroswitch-commutators, so that more channels of information could be telemetered than is the case in the usual radiosonde. It was possible to switch in three different grid resistors for the buffer amplifier, one megohm, 33,000 ohms, and 1000 ohms, so that the same voltage indication was received over a current range of 1000 to 1. The least count of the buffer amplifier was about 0.1 volt, and it saturated at about 4 volts so that the corona current range which would be covered was about 40,000 to 1. Since corona current varies approximately with the square of the field, this corresponds to an electric field range of 200 to 1. This range is by far the largest ever reported for a radiosonde.

Considerable discussion is given of the practical matter of making releases of 6-foot diameter balloons in snowstorms with high winds when a string several hundred feet long must be unwound from the radiosonde without allowing it to touch the ground.

The calibration of the calculated conversion of corona current to electric field, depends on extrapolation made at high voltages but for short lengths of conductor between the points. Mathematically the procedure is rigorous enough, but there is a belief on the part of some investigators that unmeasured corona currents flow to the sides of the trailing string below the radiosonde without being registered. If that does occur, the fields recorded by the radiosondes are too low. On the other hand, some data indicate that the effect is not a major one.

Of ten releases made during the end of the winter season in snow clouds, four yielded useful records. The principal result is that electrical effects in snowstorms are not local to the ground, as once thought. The

field commonly reversed in polarity once or twice within 10,000 feet of the ground. In one case, the potential gradient was opposite to that of the normal fair weather positive potential gradient at an altitude of 10,000 feet. The magnitudes of fields calculated were only a few hundred volts per meter. While the calibration may have been misinterpreted as referred to above, it is more likely that the weak fields observed were real, since corona current measurements made simultaneously at the ground were unusually small, about a microampere, indicating that the region traversed by the radiosonde was relatively inactive electrically.

In Chapter VI all electronic instrumentation developed for the investigations or used on them is described in detail.

The DC amplifiers used for the snowmeter work and raindrop tube experiments were developed on the project. They operated directly from the 117-volt AC supply lines. They could be used with input resistors as great as 10^{13} ohms, although usually the input resistor was about 10^{11} ohms. Full scale deflection of the recording 0-1 milliampere recorder was achieved with an input of 15 millivolts on the most sensitive range. Drift could be reduced to one millivolt per day. No amplifiers commercially available could come anywhere near these specifications. Currents of 10^{-14} amperes could be measured easily.

Various other electronic circuitry required for the snowmeter is described. Some of the special radiosonde gear is described.

The corona current amplifiers used for the corona point work are unique in that they responded to a wide range of currents of <u>both</u> polarities. The best of the circuits, referred to as the bipolar logarithmic amplifier, could cover the range from $3x10^{-9}$ to $3x10^{-4}$ amperes of both polarities, but it was actually used over a much narrower range, from $+10^{-4}$ to $+10^{-7}$ to 0 to -10^{-7} to -10^{-4} amperes, with a linear range near zero; the rest of the range is logarithmic.

VIII. RECOMMENDATIONS FOR FURTHER INVESTIGATION

Many problems in atmospheric electricity and in atmospheric physics related to electrification problems remain to be solved. Leaving out of consideration subjects quite unrelated to the work of this project such as lightning propagation, precipitation static, effects of atomic blasts on the ionization of the atmosphere, or even dynamics of thunderstorms, there are three particular but overlapping areas appropriate for discussion.

A. Electrical charge structure of thunderclouds and mechanisms of generation of charge.

B. Microscopic and submicroscopic problems associated with surfaces of liquids and solids, notably water and ice, and their relation to crystal structure, nucleus effects, droplet growth, and electrification.

C. The earth's electric field and its relation to atmospheric conductivity, air polution, precipitation, cloud structure whether thunderstorm or snow blizzard, forecasting, and nature of nuclei.

One of the principal investigations in this project was of the breaking-drop charge-production mechanism. It has been established that the magnitude of charge varies widely with conditions of disruption of drops, being great enough under favorable situations to account for all thundercloud electrification. Studies should be continued in ways that define the breaking situations in greater detail. If possible, droplets should be photographed at ultra-high speed while being disrupted to determine more about the nature of the disruption process. This technique will be difficult, but it may show why there is such wide variation in magnitude of charge.

Drops should be broken not only in field-free regions, but also under conditions of weak to strong electric fields. This experiment will not be easy either. The preliminary results on breaking of supercooled drops should be extended to eliminate any doubt regarding spray electrification of supercooled water.

If experimental means can be developed which will give fairly reproducible drop-charge characteristics, so that the wide variations observed here are overcome, then the breaking drop work should be extended to cover a range of weak solutions. By introducing known quantities of electrolytic ions, an increase may be brought about in understanding of the electrical structure of surfaces. Even today it is clear only in a general way why broken drops should liberate electrification. Control of temperature of the disruption, if associated with observation of the disruption process by photography, probably would yield significant information on means of droplet break-up.

Information is needed on the extent of small scale turbulences in thunderclouds. Whether such data can be obtained from aircraft or balloons, or whether they can be inferred from indirect effects (possibly scattering of sound or microwaves, or from trails of radioactivity or smoke), or whether the information is even accessible at all cannot be determined without more study than is represented by the mere expression of need in this paragraph. It is possible that presently existing theories, perhaps from other fields such as aerodynamics, can be applied.

A more complete and rigorous treatment of the drop-breaking-charge-production-followed-by-separation-by-an-induction-process theory of charge generation and separation should be worked out. It is possible that a critical examination of the issues will result in discovery of an initiation mechanism presently lacking in the hypothesis advanced in Chapter II.

Evidence is accumulating of the greater importance of water-processes in clouds than had been supposed. Study of water-processes and ice-processes in cloud formation and growth may be crucial in relation to the breaking drop theory of charge generation. Conversely, if the difficulties in the ice-crystal, graupel, and rapid-freezing theories can be overcome, they will acquire increased importance.

While many of the problems of surfaces have been alluded to already, there are specific problems of snow crystal formation, growth, and electrification that should be studied with particular attention to the type of crystal involved. While "pigs are pigs", and "ice is ice", in fact there are many different types of snow crystals. The snowmeter experiments intended for investigation on this project yield but one of many necessary answers to the problems of snow electrification.

While at first thought it seems natural to call for studies on natural snow, the experimental difficulties are great. Perhaps artificial snow studied in altitude chambers would be easier to work with. The snowmeter equipment certainly should be used to obtain some snow data, whether of natural or artificial snow. If used under natural conditions, the investigation should be combined with measurements of other significant electrical and meteorological parameters, for examples, measurements of the earth's electric field, and of atmospheric electrical conductivity.

The earth's electric field itself, especially under conditions of disturbed weather, has not been studied with any degree of thoroughness. While the corona-point measurements were useful in showing that the field varies greatly in magnitude, as well as in frequent reversal of sign, the corona point is at best only semi-quantitative, and furthermore it responds only to strong fields. All-weather electric field meters of the generating voltmeter type should be set up in a small network of stations so that one can distinguish changes in time at one station from changes in locations of clouds without change in their internal structure. A minimum of three stations seems to be indicated. Cornell Aeronautical Laboratory has designed and built one such all-weather equipment and has it in operation.

From the corona-point studies reported in this project, the paradox remains unexplained as to why the fields can change so rapidly in time, and yet show such coherence in time between the two points separated by 1-7 miles. For the former matter it seems that either the charged regions must

be small or they must change characteristics rapidly. For the latter point, the charged regions must be large and must change slowly. Evidently further information is needed from a small network of stations.

Measurements of the field should be combined with measurements of electrical conductivity of the atmosphere to determine whether modifications of field are due merely to inverse changes of conductivity, or whether something more fundamental is occurring. It seems essential to conduct the investigation in a sufficient number of scientific directions so that important information will not be lacking from failure to have recorded enough variables, such as electric field, conductivity, weather situation, precipitation including "capture" by photography or replica of snow type, visibility, wind, humidity, and other parameters.

The earth's field and associated electrical parameters must be characterized in part by the air mass over the region. It is possible that study of the field would yield information of value to the weather services, but it is almost certain that it will yield important information about atmospheric nuclei, many of which are accessible to measurement only by electrical means, such as conductivity measurements having considerable resolution in mobility spectra.

Investigation of these electrical parameters should not necessarily be confined to the ground. Some data already may be available in classified form from rocket soundings in New Mexico. In disturbed conditions, however, including thunderstorms and blizzards, there are only a few useful data on conditions up to easily accessible balloon altitudes. In thunderstorms, just exactly where are the charge centers relative to the freezing isotherm? If aircraft fly into electrical storms or clouds with precipitation for the purposes of obtaining electrical information they must be protected against electrostatic charge on the aircraft itself, or else the results will be meaningless. A system for maintaining zero charge on aircraft has been developed at Cornell Aeronautical Laboratory, but it is a sufficiently

involved device that it can be used only on occasional research aircraft. It is of the greatest importance that accurate values of temperature be measured rather than estimated. For this purpose the balloon-borne radiosonde is particularly useful since there is no question of its temperature accuracy.

Conditions in both thunderstorms and blizzards are still uncertain, and further investigation of them by techniques discussed in reports of this project should provide new information. As emphasized before, it is of the greatest importance that projects of this type be set up well ahead of the weather season when out-door measurements must be made. The pace on such projects should not be too high, so that the investigators can choose only the best situations for study, since cost depends only on time spent, but significance of results depends on appropriateness of the situations.

One may conclude this discussion by noting that there are many problems in the general field of atmospheric electricity that are not solved yet. Work in the direction of obtaining solutions to these problems should be accelerated.

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Note: Since there are 250 references on thunderstorms, including many on thunderstorm electricity in Meteorological Abstracts and Bibliography, volume 1, August 1950, and since there are 248 references in Chalmers: Atmospheric Electricity, 1949, the present bibliography is considerably shorter than it might otherwise have been.

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